

Title: An exergoeconomic-based parametric study to examine the effects of active and passive energy retrofit strategies for buildings

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Abstract

The paper describes a systematic framework that uses exergoeconomic theory integrated into 'building energy retrofit' (BER) design. An exergoeconomic module, based on the SPECO method, has been embedded into 'EXRETOpt', a recently developed retrofit-oriented exergy simulation tool based on EnergyPlus. Both active and passive technologies were analysed using two calibrated archetype non-domestic buildings as case studies (an office and a primary school). A novel cost-benefit indicator which accounts for building exergy destruction cost, retrofit annual capital cost, and project annual revenue is presented. This indicator is employed to account for best exergoeconomic performance technologies and to further develop deep BER packages. Compared to typical practice, exergoeconomics combined with cost-benefit provides a powerful tool for exploration and design improvement of building energy systems. In both cases, final product cost for heating and cooling processes were substantially reduced. In addition, the office case presented improvements in energy use by 67%, CO₂ emissions by 53%, thermal comfort by 22%, exergy destructions by 42%, and the overall building exergy efficiency was improved from 14.8% to 20.0%. The school case presented similar results with an improvement of building exergy efficiency from 8.2% to 11.1%, and the potential to generate income due to current government incentives.

Keywords:

exergy; exergoeconomics; building simulation; retrofits; parametric study; cost-benefit analysis.

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1. Introduction

1.1 *Energy and exergy in buildings*

In the UK, the non-domestic sector is responsible for 17% of the country's total energy use (1576.9 PJ) [1]. By 2050, the UK government has set the ambition of reducing national emissions by 80%, where the reduction of primary energy use in buildings will play a major role. However, future projections establish that the sector's footprint will increase by 200 million m², where 80% of the current stock (2015) will still be in use [2].

Building energy retrofit (BER) is a strategy that has the potential to significantly reduce sectoral emissions. Driven by current building regulations, common BER practice is still largely reliant on maximizing the thermal quality of the building envelope before HVAC system improvements are introduced. With the current high dependency on high-quality energy sources such as natural gas, oil, and off-site generated electricity, combined with the low thermodynamic efficiency of current building system technologies, new approaches to improve the selection of optimal BER measures are essential. Meggers et.al [3] established that focusing more attention on HVAC systems can provide more flexibility by creating a wider range of design possibilities through the consideration of more energy sources and technologies. Nagy et.al [4] explored the balance between insulation measures and heating system parameters to find optimal supply temperatures. The authors showed that reducing supply temperatures of the heating systems offers more potential to reduce buildings emissions than increasing the envelope insulation thickness.

As Hepbasli [5] noted, the 'Passivhaus' approach and the 'Low-exergy' approach are not mutually exclusive, since several strategies present similarities with the only limitation of the former to only be based on the thermodynamics 1st Law where the latter is based on both the 1st and 2nd Law. As any real thermodynamic process is irreversible, which means that it cannot return to original conditions due to the constant increase of entropy, exergy analysis can be performed to obtain more information on the causes and locations of these irreversibilities. Thus, exergy analysis can therefore be considered a logical approach to be applied in the design and improvement of BER.

Over the last few decades, several studies have been conducted with the aim of developing exergy methods applied to buildings [6-8]. Further studies have also applied exergy analysis for the identification of 'unconventional' opportunities to reduce dependency on high quality fuels and to minimise the gap between the quality of the supply and demand, leading to the

reduction of primary energy inputs [9-11]. For example, Esen et.al [12] presented an exergetic analysis of a GSHP working with two horizontal ground heat exchangers (HGHE) at different depths (1m and 2m). The author demonstrated that, the deeper heat exchanger (2m) had a better thermodynamic performance ($\Psi = 56.3\%$ compared to $\Psi = 53.1\%$) due to a smaller temperature lift, indicating that small variations in source temperature leads to significant reductions in primary exergy destructions. In addition, a number of studies reviewed the impact of a range of HVAC systems on building exergy performance [13-15]. Although several suggestions for improvement were presented, a main limitation highlighted the lack of appropriate economic appraisal which may lead to financially infeasible solutions.

1.2 Economics and Exergoeconomics in buildings

In BER practice, economics plays a substantial role in the decision making process where practitioners have to determine projects that minimize life cycle costs while also maximising energy savings. Life cycle cost takes into account all costs 'incurred' during the project lifespan, such as capital, operation, maintenance, and disposal. This method is useful in comparing designs with similar energy performance but with disparate economic indicators. Other useful indicators include 'Simple Payback', 'Discounted Payback', 'Profitability Index', 'Net Present Value', and 'Internal Rate of Return'. Esen et.al [16] applied these indicators to compare different conventional HVAC with a GSHP. Results showed that improved COPs combined with reduction in capital cost have made GSHP to become a more cost-effective solution in the past decade. Nevertheless, recent research has been improving these typical methods to achieve less uncertain results [17, 18]. As many researchers suggest [19-21], exergy represents the real value of an energy source, thus it should be the only rational basis for economic evaluation. Müller et.al [22] suggest that prices are a reflection of the exergy content of the specific energy carrier and the share of technology investment increases when low exergy sources are required.

Exergy analysis combined with microeconomics may potentially help improve BER design by locating the sources of inefficiencies and estimating monetary expenditure incurred as a result of exergy destructions. This combined method is known as exergoeconomics, and is commonly used in power plants and chemical processes for system optimisation. While some researchers applied exergoeconomic analysis to buildings [23-32], the analysis is often limited to only a single system design. In addition, these studies also showed that the reference temperature (normally outdoor temperature) is the most sensitive parameter, thus having the biggest effect on thermoeconomic results.

As the building sector play a fundamental part in achieving sustainable societies, there is a pressing need to rethink the way in which buildings are designed. While the current significant trend in using simulation tools for building energy design, compliance, and operation is not specifically focused on the assessment of BERs, in the past years several toolkits have been developed for this purpose [33]. And although some exergy-based building simulation tools have been created in the past decade [34-36], these lack exergoeconomic evaluation and an orientation to assess retrofit measures.

As such, the objective of this study is to exergoeconomically assess a wide range of active and passive BER measures by applying a novel cost-benefit indicator which accounts for building exergy destruction cost rate, retrofit annual capital cost rate, and project annual revenue rate. This indicator will be used for comparison among BER designs to determine best exergetic and exergoeconomic performance, and to further develop deep-BER designs. For this purpose, the expansion of EXRETOpt [37] (a recently developed retrofit-oriented exergy-based dynamic simulation tool) is necessary through the integration of an exergoeconomic analysis module.

2. Material and Methods

2.1 Simulation-based exergoeconomic framework for analysis of BER

EXRETOpt is a retrofit-oriented exergy-based tool based on EnergyPlus [38], the details of which are discussed in a previous publication by the authors [37]. For this study, a python-based model was developed to perform exergoeconomic calculations within it. The code reads selected hourly outputs from the EnergyPlus/Exergy module and creates new spreadsheets with exergy and exergoeconomic indicators. The expanded tool is capable of providing 350+ thermodynamic and non-thermodynamic indicators. Fig. 1 illustrates the design framework and procedure for the integration of exergoeconomic analysis into BER modelling practice. The diagram also shows the modelling environments utilised at each stage of the framework.

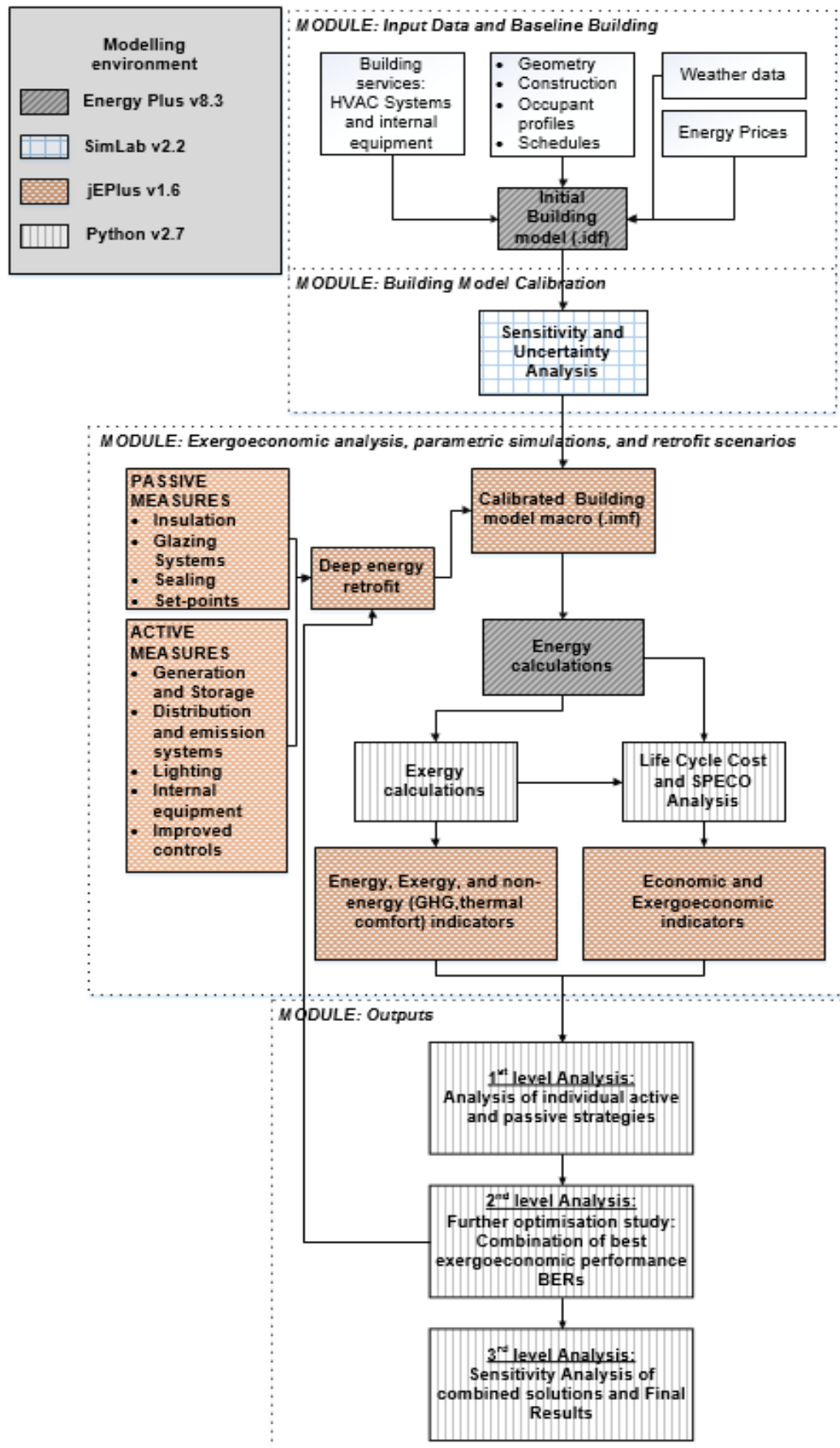


Fig. 1 Design framework for exergoeconomic-based retrofit analysis [37]

2.2 Energy and Exergy analysis

The building thermal exergy method used in the modelling process is mainly based on the developments proposed by Schmidt [7] and Torio [8] and implemented in the IEA ECB Annex 49 [36]. The method utilises an input-output approach based on seven different subsystems to calculate the variables throughout the energy supply chain. Previously, EXRETOpt has implemented these equations for dynamic building simulation by using python scripts. In addition, EXRETOpt is also capable of calculating exergy destructions on the DHW system level, refrigeration, cooking, and all electric-based equipment, thus allowing for a holistic exergy assessment. For electric-based equipment, Table 1 shows the model assumptions for energy and exergy efficiency:

Table 1 Exergy efficiency values for electric-based devices [39]		
Equipment	Energy Efficiency (%)	Exergy efficiency (%)
Motors	80-87	80-87
Fuel cell system	33	33
CHP	74	31
Solar photovoltaic	6-25	6-25
Solar thermal	10-30	10-30
Small wind turbines	20-40 [40]	19-29 [41]
Electric battery (lead-acid)	75-85	75-85
Pumps	60-70 [42]	58-67 [42]
Fans	55-80 [42,43]	50-68 [42,44]
Resistance space heater	99	6
Lighting fluorescent and LED	20	20
Electric-based catering	85	50
Internal/office equipment	70	70

This holistic method provides comprehensive means by which to understand the interactions between the building envelope and the building energy services. For a better interpretation, thermodynamic assessments typically require an input-output abstraction of all the subsystems that interact in the whole energy process (Fig. 2). The basic formulas for guidance are presented in the following section.

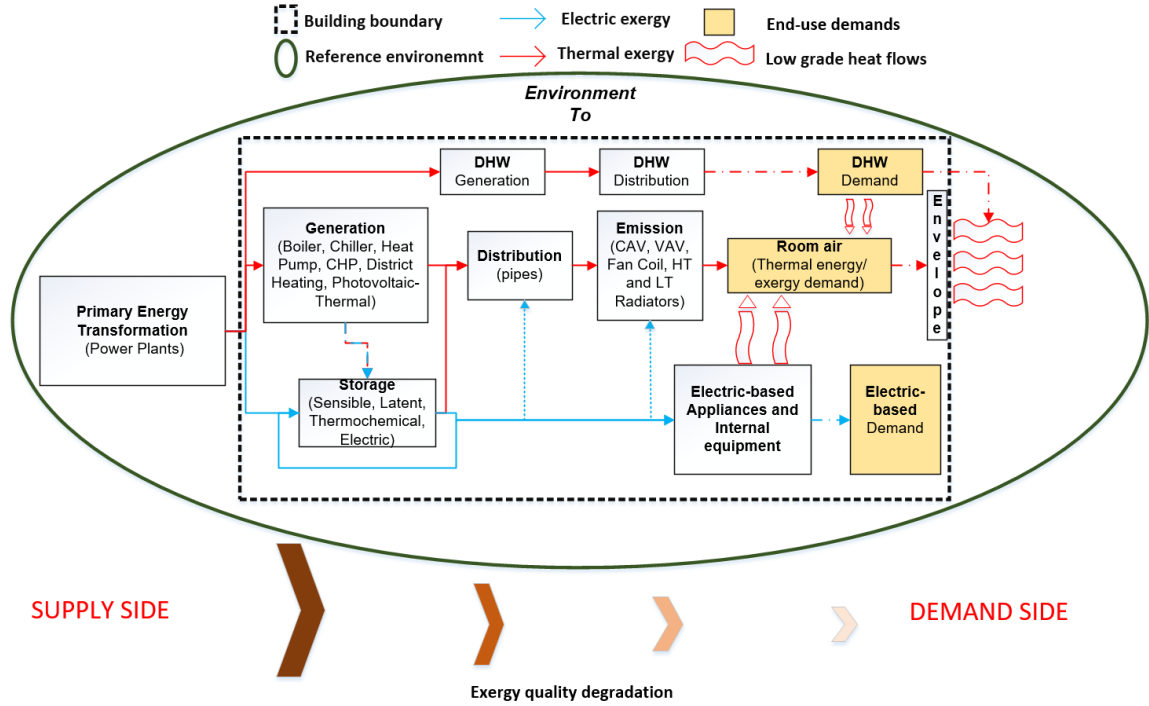


Fig. 2 Energy supply chain and subsystems for exergy calculations. Based on the IEA ECB Annex 49 method calculation.

2.2.1 Exergy demand and irreversibilities calculation

The total exergy demand at the building level $Ex_{dem,bui}$ is obtained by adding all the demands for each end-use:

$$Ex_{dem,bui} = \sum Ex_{dem,end\ use,ith} \quad (1)$$

where $Ex_{dem,end\ use}$ is the exergy demand by end-use.

After calculating the total demand, the model calculates irreversibilities at each subsystem level. Ex_{prim} , the exergy input at the primary energy transformation subsystem is analysed and the impact of using different types of energy sources are distinguished as follows:

$$Ex_{prim}(t_k) = \sum_i \left[\frac{En_{gen,i}(t_k)}{\eta_{gen,i}(t_k)} * F_{p,source,i} * F_{q,source,i} \right] \quad (2)$$

where, En_{gen} is the energy source used by the building HVAC generation system (chiller, boiler, CHP), η_{gen} is the system efficiency, $F_{p,source}$ is the UK primary energy factor [45] and $F_{q,source}$ is quality factor of the fuel [36]. These factors are shown in Table 2.

Table 2 Primary Energy Factors and Quality Factors by energy sources [36,45]

Energy source	Primary energy factor (F_p) (kWh/kWh)	Quality factor (F_q) (kWh_ex/kWh_en)
Natural gas	1.11	0.94
Electricity (Grid supplied)	2.58	1.00
District Energy ¹	1.11	0.94
Oil	1.07	1.00
Biomass (Wood pellets)	1.20	1.05

The total exergy destructions Ex_{dest} , are calculated as follows

$$Ex_{dest} = Ex_{prim} - Ex_{dem,bui} \quad (3)$$

Finally, the building exergy efficiency Ψ_{bui} is obtained as follows:

$$\Psi_{bui} = \frac{Ex_{dem,bui}}{Ex_{prim}} \quad (4)$$

2.2.2 Exergy analysis of renewable systems

As technologies considered in this analysis such as photovoltaic panels, solar collectors, hybrid PV/T, and ground/air source heat pumps require a different exergy analysis, the tool was expanded to integrate renewable-based technologies. The equations to incorporate this were based on a comprehensive review of exergy analysis for renewable-based systems undertaken by Torío et.al [46] and described in the calculation method in Appendix A.

2.2.3 The reference environment

Although widely discussed, the majority of the research considers the outdoor air as the most appropriate reference environment for the analysis [36]. Pons [47] considers that the dynamism of the reference environment and the time-dependency may not be the best choice. As such, the use of a static reference temperature through the consideration of a linear

¹ The District system was assumed to be run by a single-effect indirect-fired absorption chiller with a coefficient of performance (COP) of 0.7.

combination between entropy generation multiplied by a constant temperature is more appropriate. This presents an advantage, as entropy does not depend on temperature but only on the state of the system. Other authors consider that the dynamism of the 'dead-state' has to be accounted for, where the use of dynamic temperature is more appropriate, especially if dehumidification and cooling processes exist within the building [48-50]. In this study, the dynamic simulation approach is applied.

2.3 Retrofit measures and cost database

As building energy efficiency can usually be improved by both passive and active technologies, a comprehensive BER database was compiled. This included active retrofit designs such as HVAC, lighting, and renewable energy generation systems, as well as passive solutions such as envelope insulation, glazing systems, air-leakage improvement, and heating and cooling set points variation. The solutions were implemented by developing individual '.idf files' (EnergyPlus files) combined through the use of the EnergyPlus Macro function, and then 'handled' by jEPlus software [51] to undertake the final simulation. To support the economic analysis, prices must be properly defined. These were obtained from a wide range of databases such as 'Spons' manuals [52, 53], DECC [54], NREL [55], RSmeans [56], webstores [57], and academic publications [58, 59]. As EnergyPlus has the capability to auto-size any equipment, prices are provided per unit (either kW or by m²) since the model automatically calculates the total capital price for either individual or combined measures. The list of technologies, variables, and prices² for all retrofit measures is detailed in Appendix B.

2.4 Economic and Exergoeconomic analysis

2.4.1 Net Present Value (NPV) and Discounted Payback Period (DPB)

For BER, NPV indicates the present value of an investment based on expected energy savings costs minus the cost of the project, where a positive NPV value represent financial viability. Despite some limitations, especially due to future uncertainty, NPV is the most widely used

² If prices for some measures were not in local currency (GBP), conversion rates from 25th-October-2015 were considered.

technique for BER assessment [18], as it provides a more realistic representation of the future value of money. NPV is calculated as follows:

$$NPV_{Nyears} = -TCI + \left(\sum_{n=1}^N \frac{R}{(1+i)^n} \right) + \frac{SV_N}{(1+i)^N} \quad (5)$$

where TCI is initial total capital investment, R is the annual revenue costs (composed by the annual energy cost savings minus the operation and maintenance cost), and SV is the salvage cost or residual value with measures with longer lifespan (we have considered a common rate of 15%). In this study, a lifespan (N) of 50 years and a discount rate (i) of 3% [60] were considered.

DPB provides the number of years to the break-even point by also considering the future value of money. Thus, to calculate DPB period we used the following formula [61]:

$$DPB = - \frac{\ln \left[\left((1-(1+i)) * \left(\frac{TCI}{R} \right) \right) + 1 \right]}{\ln(1+i)} \quad (6)$$

2.4.2 Energy Prices and Incentive Programs

The economic module considers average fuel prices for the corresponding building size. These were obtained from the government bulletin quarterly energy prices for September 2015 [62] and are shown in Table 3. In addition, an annual energy price escalation was included for all energy sources based on the previous ten years.

Table 3 Energy tariffs in the UK in 2015 (considering CCL³) [62]

Energy source	Prices (£/kWh)
<i>Natural gas</i>	0.030
<i>Electricity (Grid supplied)</i>	0.121
<i>District Energy</i>	0.066
<i>Oil</i>	0.054
<i>Biomass (Wood pellets)</i>	0.044

³ CCL is a tax for some energy sources delivered to non-domestic users where the tax aim is to incentivise users to install energy efficient technologies.

Moreover, government incentives that provide financial help to certain ‘renewable’ and ‘low carbon’ technologies were included. Depending on the project, this could play a major role in the financial viability of some BER designs. The two main government incentives are: Feed-in Tariff (FiT) and the Renewable Heat Incentive (RHI). FiT is a grant scheme that focuses on renewable electricity generation technologies such as mCHP, wind turbines, and photovoltaic panels; while RHI is a grant scheme focused on the implementation and use of renewable heat, prioritizing technologies such as biomass/biogas heating, heat pumps, and solar collectors. Whilst these incentives are constantly changing, for this analysis we have considered tariffs from October 2015 (Table 4).

Table 4 UK Government subsidies in 2015

Incentive Schemes Tariff	Prices (£/kWh)
<i>FiT Electricity Exported</i>	0.048
<i>FiT PV Electricity Generation</i>	0.059
<i>FiT Wind Electricity Generation</i>	0.138
<i>RHI Solar Heat Generation</i>	0.103
<i>RHI GSHP Heat Generation</i>	0.090
<i>RHI ASHP Heat Generation</i>	0.026
<i>RHI Biomass Heating Generation</i>	0.045

2.4.3 Exergoeconomic module

When costs are not allocated appropriately, it becomes difficult to assess the actual cost effectiveness of a measure, especially when multiple products exist, as is in the case of buildings [63]. Therefore, the typical economic analysis was expanded to include an exergoeconomic evaluation module. The chosen exergoeconomic method was “SPECOC” (specific exergy cost), initially developed by Tsatsaronis [20] and further improved in Lazzaretto and Tsatsaronis [64]. The SPECOC method is based on the calculation of exergy efficiencies, exergy destructions, exergy losses, and exergy ratios at a component level. After quantifying the energy and exergy streams through the energy supply chain, a definition of fuel(s) and product(s) for each component has to be constructed where cost balance equations have to be applied. A representation of the analysis can be seen in Fig. 3.

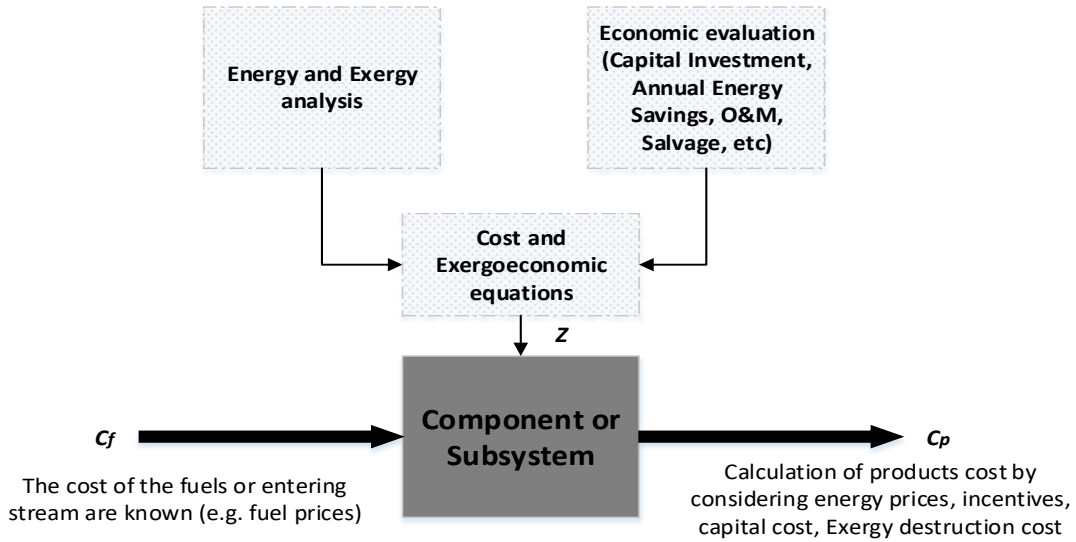


Fig. 3 General representation of a cost-balance and exergoeconomic analysis in an energy component

The SPECO method and the 'LowEx' building approach has been previously applied by Yücer and Hepbasli [23] and Baldvinsson and Nakata [65], locating the product cost formation for the heating stream throughout the energy supply chain. However, in this research our model is able to perform exergoeconomic analysis of for four different streams (heating, cooling, DHW, and electric-based equipment), as well as a thermoeconomic life cycle cost of a running building with a specific retrofit project. Fig. 4 presents a schematic block diagram of the subsystems and streams that were analysed in this research.

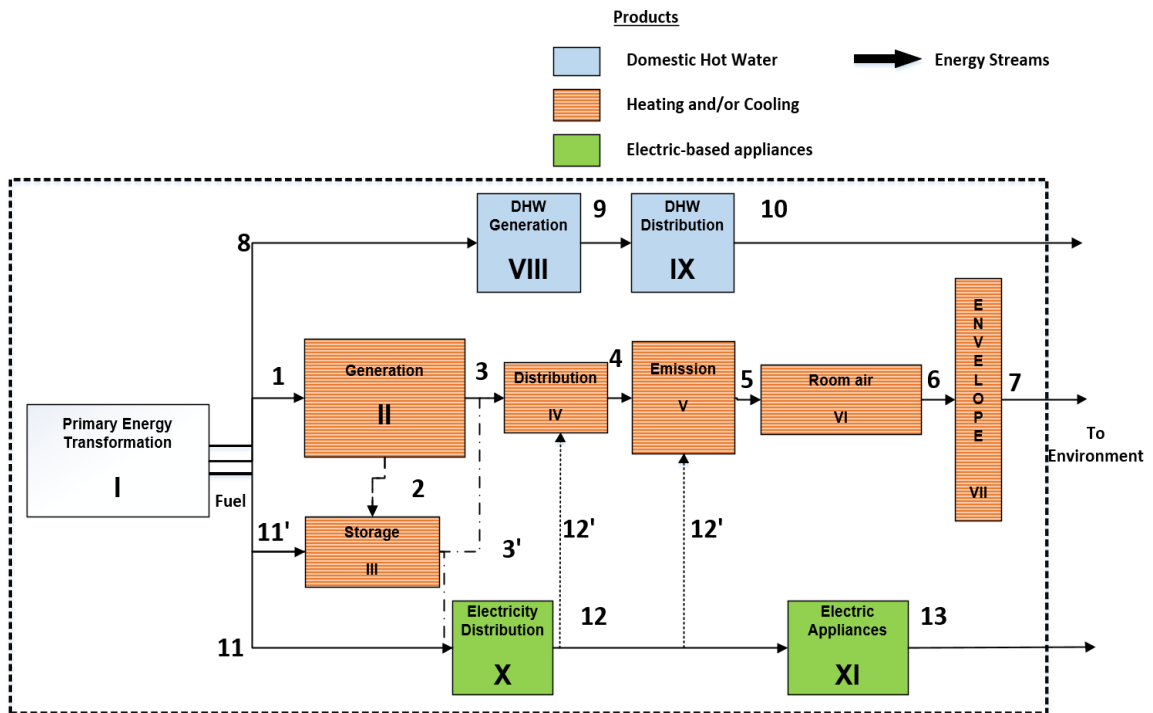


Fig. 4 Schematic diagram of energy supply subsystems and energy streams in a building (HVAC, DHW, and electric appliances)

The exergy cost of a product (P) can be regarded as the exergy content plus the sum of irreversibilities along the process. As exergy destructions directly affects the cost of the products, whilst being consumed along the process, the product's exergy cost inevitably increases. The value depends on two factors: the amount of destructions and the current price of the entering stream (fuel). The most important cost equations from the SPECO method are summarized below.

First, the general exergy balance can be written as follows:

$$\dot{Ex}_{F,k} = \dot{Ex}_{P,k} + \dot{Ex}_{D,k} \quad (7)$$

where $\dot{Ex}_{F,k}$, $\dot{Ex}_{P,k}$, and $\dot{Ex}_{D,k}$ are the fuel exergy, product exergy, and exergy destruction of the component k, respectively.

An exergy cost stream \dot{C}_i associated with the corresponding stream i is calculated as follows:

$$\dot{C}_i = c_i \dot{Ex}_i \quad (8)$$

where c_i and \dot{Ex}_i are the stream's specific cost and exergy, respectively.

By combining exergy balance and thermoeconomics, we obtain the general cost balance expression. Where the exergy cost balance $\dot{C}_{p,k}$ related to a subsystem is expressed as follows:

$$\dot{C}_{p,k} = \dot{C}_{D,k} + \dot{Z}_k \quad (9)$$

Where $\dot{C}_{D,k}$ and \dot{Z}_k is the exergy destruction cost and sum of capital investment rate for the component k , respectively. In addition, the exergy destruction cost of a component $\dot{C}_{D,k}$ is defined as:

$$\dot{C}_{D,k} = c_{f,K} \dot{Ex}_{D,k} \quad (10)$$

where $c_{f,K}$ and $\dot{Ex}_{D,k}$ are the fuel cost and exergy destructions for the component k , respectively. To obtain building total exergy destruction cost, a sum of all subsystems components has to be done:

$$\dot{C}_{D,sys} = \sum_{k=0}^n (c_{f,K} \dot{Ex}_{D,k}) \quad (11)$$

To account for the component capital investment Z_k , we converted it into an hourly rate, dependant on the project's lifetime. This is done by using Eq. 12:

$$\dot{Z}_k = \frac{PW \cdot CRF}{\tau} \quad (12)$$

where PW is the present factor of the retrofit measure, CRF is the capital recovery, and τ is the equipment annual working hours. PW and CRF are obtained by using Eq. 13 and 14 respectively:

$$PW = TCI - \frac{SV_N}{(1+i)^N} \quad (13)$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (14)$$

Table 5 shows the exergy and exergoeconomic balance used in the model. By solving these equations, the cost of energy streams and the economic impact by subsystem are obtained. Outputs are presented as average cost per unit (£/kWh).

Table 5 Exergoeconomic balance for subsystems and streams

No.	Subsystem	Exergy Fuel	Exergy Product	Exergoeconomic balance
I	Primary Energy Transformation	$F_I = (\text{Raw energy sources})$	$P_I = \dot{E}x_1$	$\dot{C}_0 + \dot{Z}_I = \dot{C}_1$
II	Generation	$F_{II} = \dot{E}x_1$	$P_{II} = \dot{E}x_2 + \dot{E}x_3$	$\dot{C}_1 + \dot{Z}_{II} = \dot{C}_2$
III	Storage	$F_{III} = \dot{E}x_2 + \dot{E}x_{11'}$	$P_{III} = \dot{E}x_{3'}$	$\dot{C}_2 + \dot{C}_{11} + \dot{Z}_{III} = \dot{C}_3$
IV	Distribution	$F_{IV} = \dot{E}x_3 + \dot{E}x_{3'} + \dot{E}x_{12'}$	$P_{IV} = \dot{E}x_4$	$\dot{C}_3 + \dot{C}_{12'} + \dot{Z}_{IV} = \dot{C}_4$
V	Emission	$F_V = \dot{E}x_4 + \dot{E}x_{12'}$	$P_V = \dot{E}x_5$	$\dot{C}_4 + \dot{C}_{12'} + \dot{Z}_V = \dot{C}_5$
VI	Room Air	$F_{VI} = \dot{E}x_5$	$P_{VI} = \dot{E}x_6$	$\dot{C}_5 + \dot{Z}_{VI} = \dot{C}_6$
VII	Envelope	$F_{VII} = \dot{E}x_6$	$P_{VII} = \dot{E}x_7$	$\dot{C}_6 + \dot{Z}_{VII} = \dot{C}_7$
VIII	DHW Generation	$F_{VIII} = \dot{E}x_8$	$P_{VIII} = \dot{E}x_9$	$\dot{C}_8 + \dot{Z}_{VIII} = \dot{C}_9$
IX	DHW Distribution	$F_{IX} = \dot{E}x_9$	$P_{IX} = \dot{E}x_{10}$	$\dot{C}_9 + \dot{Z}_{IX} = \dot{C}_{10}$
X	Electricity Distribution	$F_X = \dot{E}x_{11} + \dot{E}x_{3'}$	$P_X = \dot{E}x_{12}$	$\dot{C}_{11} + \dot{C}_{3'} + \dot{Z}_X = \dot{C}_{12}$
XI	Electric Appliances	$F_{XI} = \dot{E}x_{12}$	$P_{XI} = \dot{E}x_{13}$	$\dot{C}_{12} + \dot{Z}_{XI} = \dot{C}_{13}$

In addition, two additional performance indicators were calculated: the *relative cost difference* and the *exergoeconomic factor*. These are especially useful for comparison of different BER design options. The relative cost difference r_k is calculated as follows:

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \quad (15)$$

Where $c_{P,k}$ is the average cost of the product and $c_{F,k}$ is the average cost of fuel at the component k . The indicator shows the increase in product price compared to the price of the entering stream (fuel).

The exergoeconomic factor f_k shows the ratio of the component capital cost to the component's 'total cost'. The 'total cost' consists on capital cost, O&M cost, and exergy destructions cost. This is obtained as follows:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k}(\dot{E}x_{D,k})} \quad (16)$$

The outputs highlight the principal source of a component's expenditure. If the value is close to one it means that component's capital cost is the main origin of expenditure, while if the value is close to zero it means that exergy destruction cost it is the main source of expenditure. This is useful, as it allows the practitioner to choose between reducing the necessary capital investment for the component/system or to focus on increasing component exergy efficiency.

As typical economic cost-benefit assessment does not consider exergy destructions, and with the aim of integrating exergoeconomic evaluation in typical economic analysis for buildings, the SPECO method was extended in this study through the inclusion of a new indicator: the *exergoeconomic cost-benefit index* $Exec_{CB}$, calculated as follows:

$$Exec_{CB} = \dot{C}_{D,sys} + \dot{Z}_{sys} - \dot{R} \quad (17)$$

where $\dot{C}_{D,sys}$ is the building total exergy destruction cost rate (eq. 15), \dot{Z}_{sys} is the annual capital cost rate for the retrofit measure (eq. 16), and \dot{R} is the annual revenue rate. The revenue is calculated based on the project's lifetime and considering the present value of money. The outputs are given in £/h. For BER analysis, a benchmark value is first calculated for the baseline building. For the base case, this indicator only includes exergy destruction costs $\dot{C}_{D,sys}$ as no retrofit measure (\dot{Z}_{sys}) has been applied and consequently no revenue (\dot{R}) has been generated. After the retrofit analysis is performed, if the retrofitted building presents a $Exec_{CB}$ lower than the baseline $\dot{C}_{D,sys}$, the design represents both a cost-effective solution and an improvement in exergy performance.

2.5 Other non-thermodynamic parameters

To account for occupant thermal comfort the "Thermal Comfort Not Comfortable Time" outputs calculated directly by EnergyPlus were used. This value is based on the ASHRAE 55-2004

method [66], and provides the number of hours per year that internal conditions are not in the summer or winter clothes region. This method considers the combination of humidity ratio and operative temperature with personal factors (physical, adaptive, and organismic) that will produce acceptable conditions to 80% or more occupants within the building.

For the analysis of the carbon footprint (CO₂ emissions), only emissions due to energy use during building's lifetime operation were considered, thus technology embodied emissions (including embodied exergy) were neglected in this research. The emission factors for different fuels used are shown in Table 6.

Table 6 Emission factors for different energy sources	
Energy source	kgCO₂e/kWh
<i>Natural gas (Boiler, CHP, District)</i>	0.212
<i>Electricity (grid)</i>	0.522
<i>Fuel oil</i>	0.313
<i>Biomass (Wood pellets)</i>	0.039
<i>PV/T electricity and solar thermal</i>	0.075
<i>Wind electricity</i>	0.038

For future years, a moderate future electricity linear decarbonisation was considered, going from the current value of 0.522 to a value of 0.20 kgCO₂e /kWh by the end of the analysis period (50 years). The factors for the other fuel types were assumed as constant.

3. Case Studies and baseline values

3.1 Building energy model calibration

The case studies are based on two typical non-domestic buildings located in the UK (an office and a primary school). The sources for the archetype development as well as main characteristics have been presented in previous research [37]. The buildings were assumed to be built before first building energy regulations were implemented prior to 1965. The HVAC systems were selected to be representative of those installed in these building types and ages [67] and the London-Gatwick weather file was used as the reference environment.

A comprehensive sensitivity and uncertainty analysis was performed to calibrate the building models to national mean values for electricity and gas use in non-domestic buildings [68-70]. Two-hundred different models were created by sampling eight parameters that have significant impact on energy utilisation [71]: 1) lighting power density, 2) equipment power density, 3) building orientation, 4) envelope thermal conductivity, 5) air tightness, 6) occupant density, 7) set point controls, and 8) HVAC system efficiency. The calibration procedure was implemented through the use of the Latin hypercube sampling method combined with Monte Carlo analysis within SimLab 2.2 [72] software environment. All the simulated buildings (in blue) and the selected baseline model (in red) for both archetypes are illustrated in Fig. 5. The baseline building characteristics for both models are presented in Table 7.

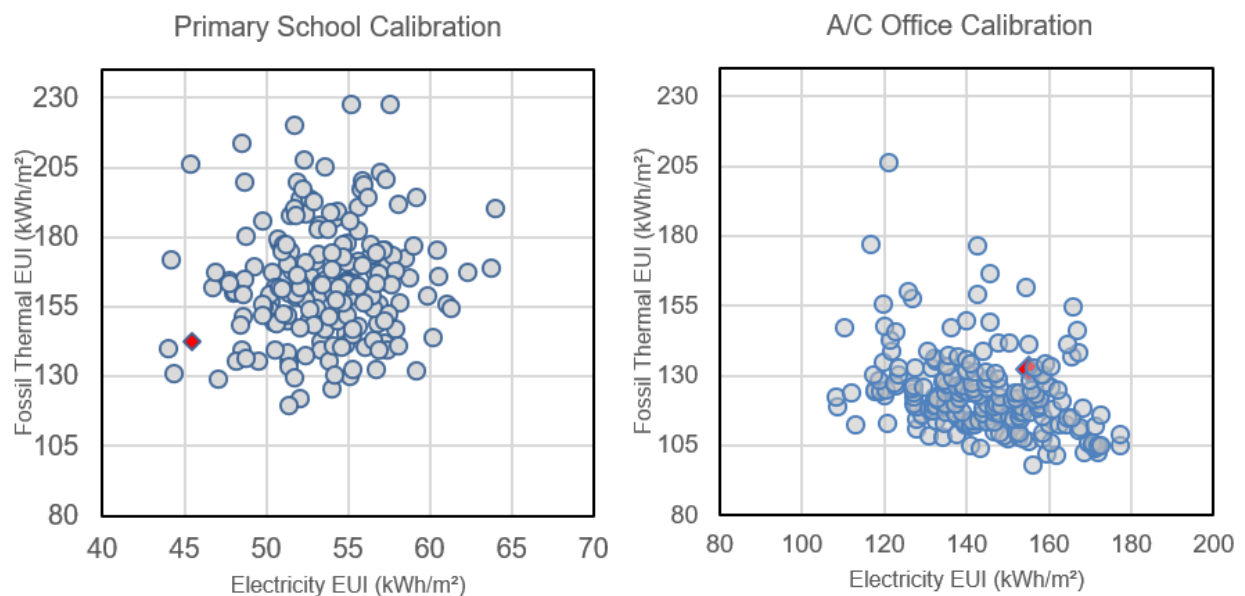


Fig. 5 Simulation cases from Latin Hypercube Sampling

Table 7 Case studies baseline characteristics

Baseline characteristics	Primary School	A/C Office
<i>Year of construction</i>	1960s	1960s
<i>Number of floors</i>	2	3
<i>Floor space (m²)</i>	1990	2590
<i>Orientation (°)</i>	227	31
<i>Air tightness (ach)</i>	1.0	1.0
<i>Exterior Walls</i>	Cavity Wall-Brick walls 100 mm brick with 25mm air gap (U-value=1.66 W/m ² K)	Cavity Wall-Brick walls 100 mm brick with 25mm air gap (U-value=1.61 W/m ² K)
<i>Roof</i>	200mm concrete block (U-value=3.12 W/m ² K)	200mm concrete block (U-value=3.12 W/m ² K)
<i>Ground floor</i>	150mm concrete block (U-value=1.31 W/m ² K)	150mm concrete block (U-value=1.31 W/m ² K)
<i>Windows</i>	Single-pane clear (5mm thick)	Single-pane clear (5mm thick)
<i>Glazing ratio</i>	28%	41%
<i>HVAC System</i>	515 kW Gas-fired boiler (η= 82%)	750 kW Gas-fired boiler (η = 70%) Air-based Chiller 272 kW (COP=2.0)
<i>Emission system</i>	Heating: HT Radiators 90/70°C Cooling: Natural ventilated	Heating: CAV 80/50°C Cooling: CAV 7/12°C
<i>Heating Set Point (°C)</i>	19.3	21.9
<i>Cooling Set Point (°C)</i>	--	24.0
<i>Occupancy (people/m²)*</i>	2.1	8.2
<i>Equipment (W/m²)*</i>	2.0	14.9
<i>Lighting level (W/m²)*</i>	12.2	21.4
<i>EUI electricity (kWh/m²-y)</i>	45.6	158.3
<i>EUI gas (kWh/m²-y)</i>	142.3	130.2
<i>Annual energy bill (£/y)</i>	19449	59625
<i>Thermal discomfort (hours)</i>	1443	1413
<i>CO2 emissions (Ton)</i>	214.8	285.6

*Just for main areas. School: Classrooms and Staff offices. A/C Office: Open plan office space

3.2 Exergetic and exergoeconomic baseline values

3.2.1 Exergy destructions per end-use

To highlight the differences between the building types, the share of destructions per component were analysed (Fig. 6). In the office case, the largest share of irreversibilities occurs in the generation of electricity used for electric-based appliances (51%), followed by the HVAC generation subsystem (23%) as a result of burning gas for heating purposes. In the school case, the HVAC generation subsystem presents the largest destruction per end-use (41%). For both buildings, the HVAC “primary energy transformation” subsystem exergy destructions are rather low, although in the office it represents a larger share due to the use of electricity for cooling process during summer.

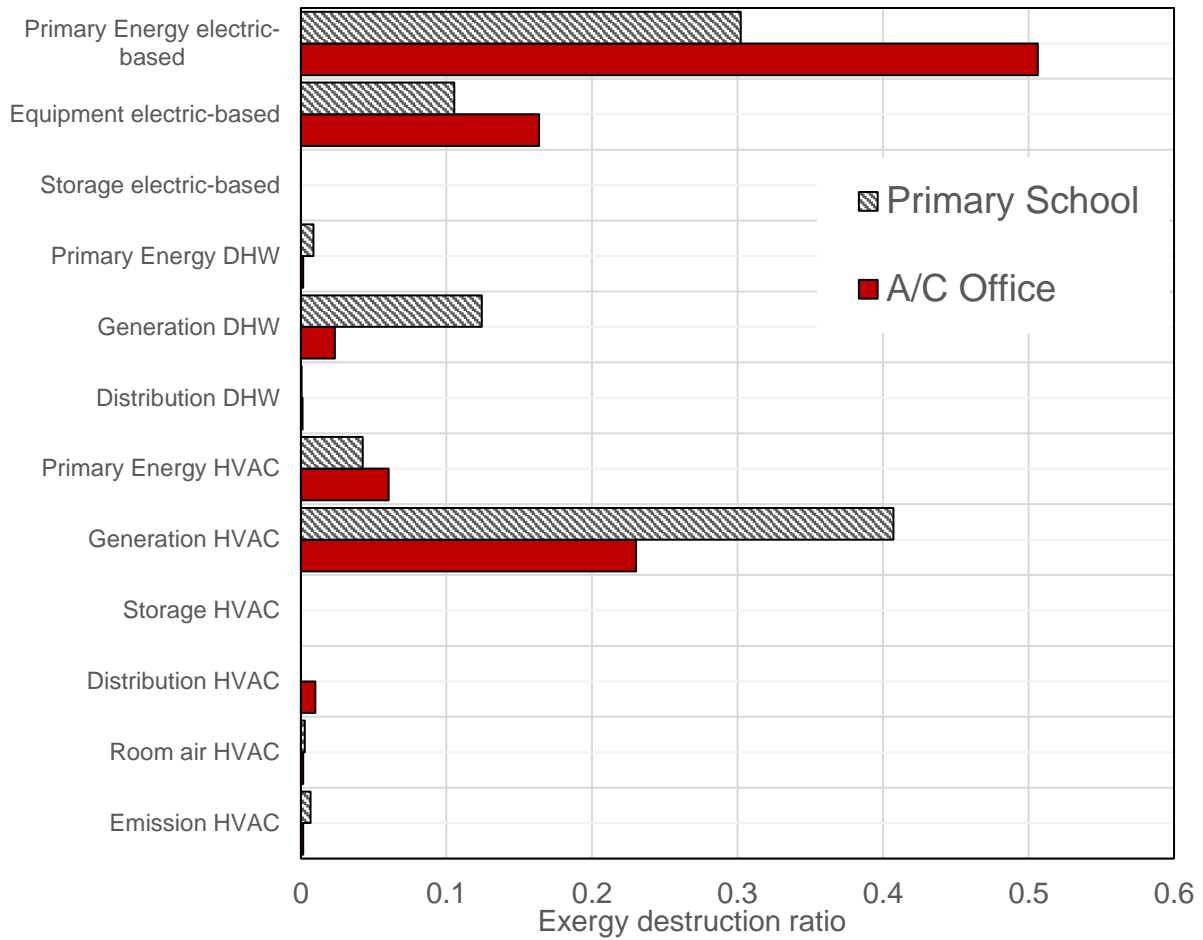


Fig. 6 Exergy destruction ratio of all energy subsystems for both buildings

3.2.2 Baseline exergoeconomic indicators

Fig. 7-9 illustrate exergy destruction accumulation compared to the stream cost formation through the HVAC supply chain. Fig 7 shows how the school heating product at the end of the energy supply chain increases from £0.03/kWh (gas price) to £1.79 £/kWh, with a total relative cost difference r_k of 58.66. The largest increase occurs at the generation (gas boiler) and envelope subsystems.

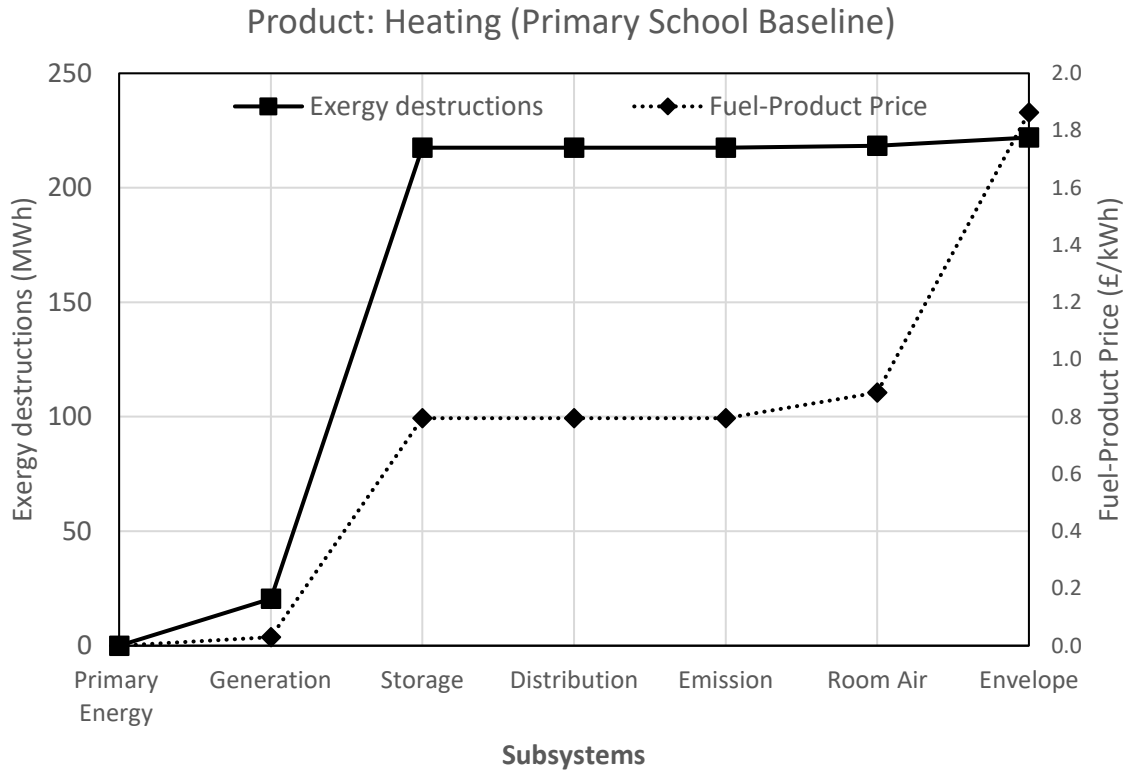


Fig. 7 Exergy destruction accumulation vs product cost formation for heating stream. Primary School

For the office case it is possible to show the streams for the two thermal products: heating and cooling. In Fig. 8, the heating product in the office increased from £0.03/kWh to £0.45/kWh, having a total relative cost difference r_k of 13.9. In this case, the generation and distribution subsystems are areas of concern. For the cooling product (Fig. 9), exergy cost starts at £0.12/kWh (electricity price) and increases up to £3.10/kWh ($r_k = 24.9$). Attention has to be put to the generation (low efficient chiller), the distribution, and emission systems, where the biggest cost increases were found.

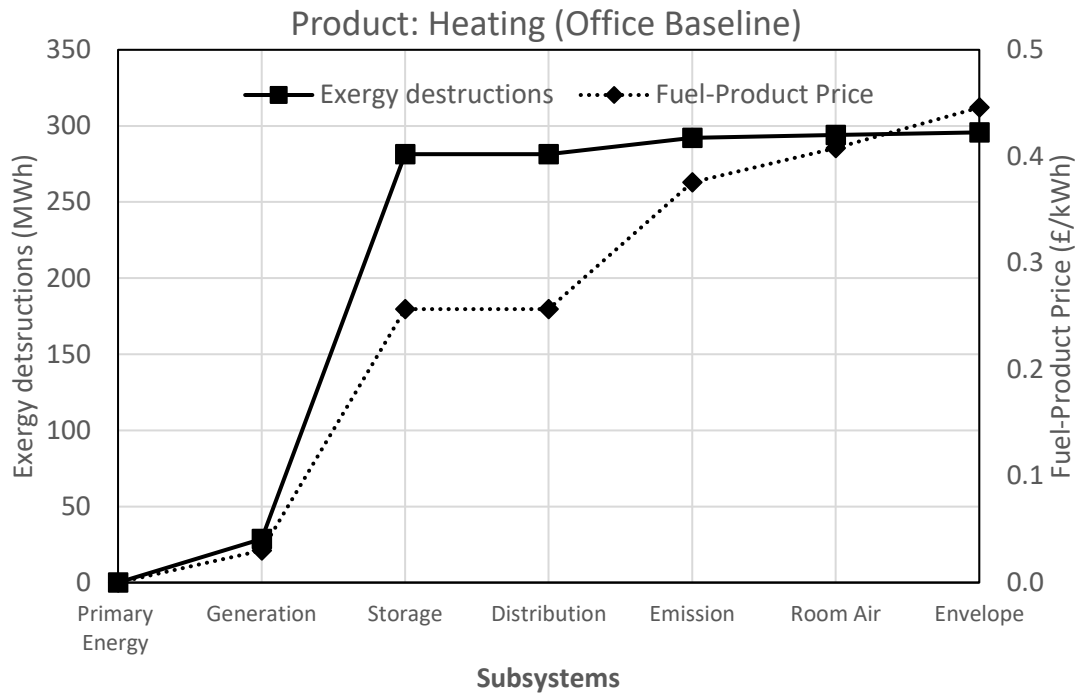


Fig. 8 Exergy destruction accumulation vs product cost formation for heating stream. A/C Office

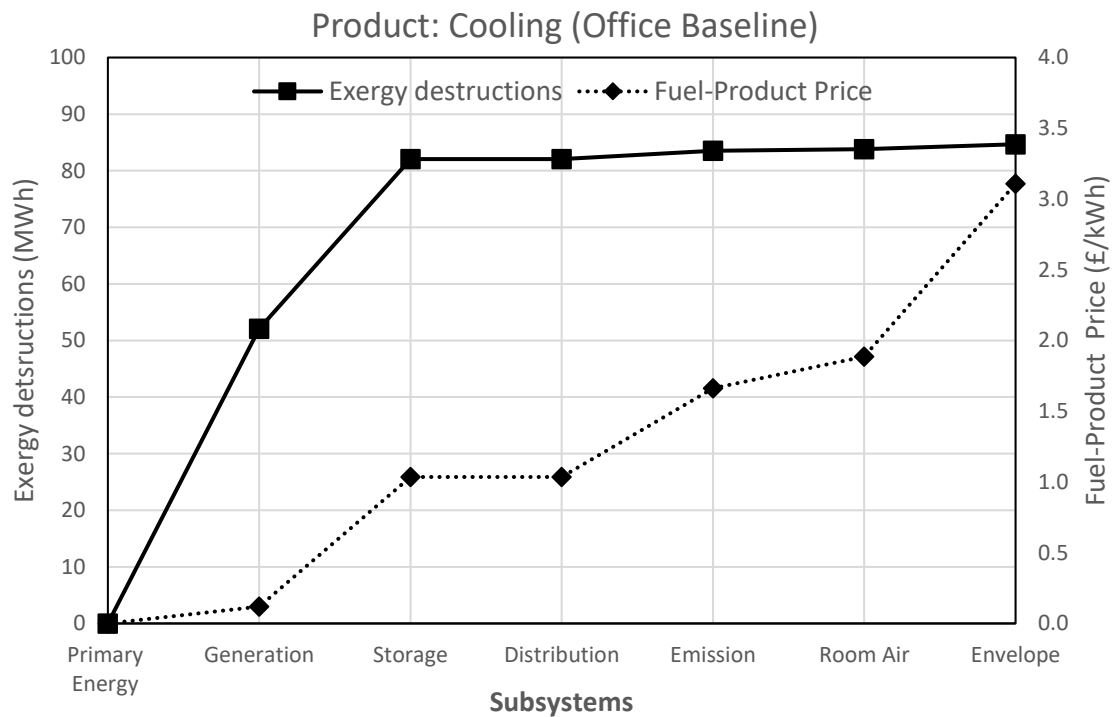


Fig. 9 Exergy destruction accumulation vs product cost formation for cooling stream . A/C Office

In many cases exergy cost for heating and cooling products can differ dramatically, as the exergy cost significantly depends on temperatures. In this sense, cooling processes by working closer to ambient temperature (thus having a small ΔT), any exergy destructions are

highly penalised in exergy/exergoeconomic analyses. Added to this, the conversion efficiency of any subsystem can also have a big impact on the final product price. This fuel-product analysis was done for all streams (heating, cooling, DHW, and electric appliances). Baseline exergoeconomic values for both buildings can be seen in Table 8.

Table 8 Baseline buildings exergoeconomic values

Baseline characteristics	Primary School	Office
<i>Exergy input (fuel) (MWh)</i>	533.0	1440.8
<i>Exergy demand (product) (MWh)</i>	43.5	212.6
<i>Exergy destructions (MWh)</i>	489.4	1228.2
<i>Exergy efficiency HVAC</i>	1.5%	5.1%
<i>Exergy efficiency DHW</i>	6.2%	8.7%
<i>Exergy efficiency Electric equip.</i>	15.1%	18.9%
<i>Exergy efficiency Building</i>	8.2%	14.8%
<i>Exergy cost fuel-prod HEAT (£/kWh) $\{r_k\}$</i>	0.03—1.86 {61.11}	0.03—0.45 {13.86}
<i>Exergy cost fuel-prod COLD (£/kWh) $\{r_k\}$</i>	----- {---}	0.12—3.11 {24.89}
<i>Exergy cost fuel-prod DHW (£/kWh) $\{r_k\}$</i>	0.03—0.44 {13.72}	0.03—0.55 {17.49}
<i>Exergy cost fuel-prod Elec (£/kWh) $\{r_k\}$</i>	0.12—0.31 {1.60}	0.12—0.25 {1.07}
<i>D Exergy destructions cost (£/h) [energy bill £; % D from energy bill]</i>	2.72 {18432.6; 94.7%}	6.54 {44,661.0; 74.9 %}
<i>Z (£/h)</i>	0	0
<i>Exergoeconomic factor f_k (%)</i>	1	1
<i>Exergoeconomic cost-benefit (£/h)</i>	2.89	6.54

As discussed in section 2.4.3, the expanded exergoeconomic cost-benefit indicator for the baseline cases is the same as the building cost exergy destructions ($Exec_{CB} = \dot{C}_{D,sys}$) as no retrofit strategy has been implemented. For the school, this has a value of £2.89/h and for the office is £6.54/h. In the case of the school, exergy destructions costs represent around 95% of the annual energy expenditure, while in the office is close to 75%. Fig. 10 shows a detailed evaluation of exergoeconomic cost by locating the destruction cost share per product.

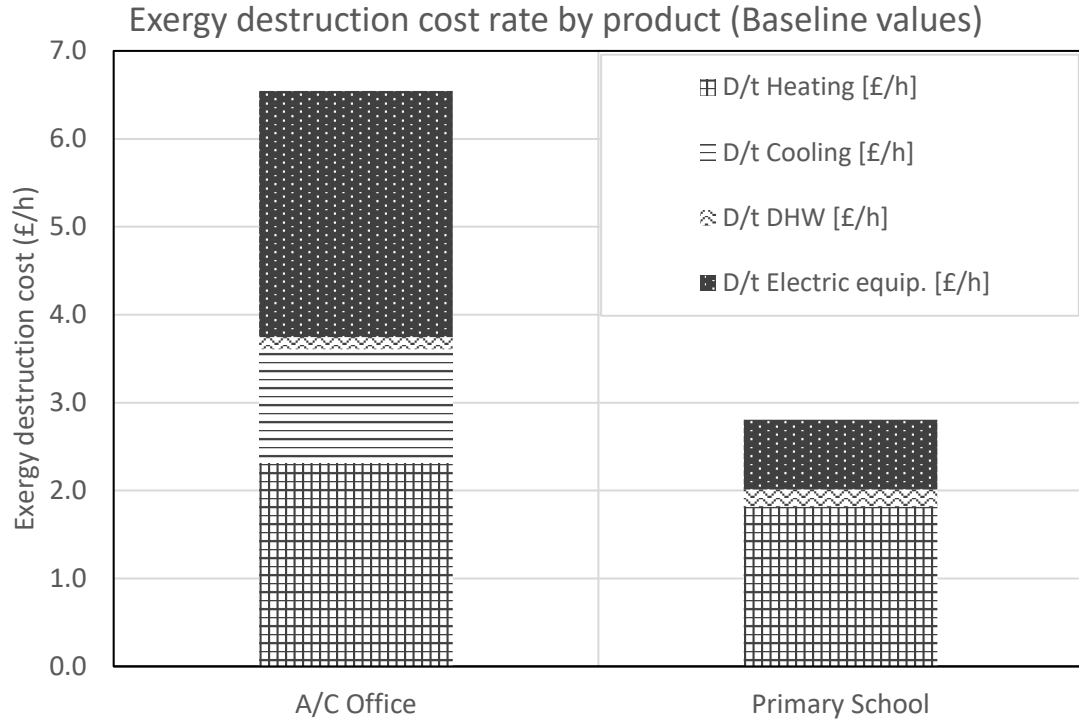


Fig. 10 Exergy destruction cost rate per product type (Baseline)

By considering a trade-off between exergy destruction cost, project capital cost, and annual revenue, a good exergoeconomic-based BER design will present lower values of $Exec_{CB}$ than the baseline $\dot{C}_{D,sys}$ value.

4. Results and Discussions

Both $Exec_{CB}$ and thermal comfort conditions indicators were used to explore the best retrofit solutions for the two case studies. In some cases, capital investment and NPV were also considered to inform whether the retrofit measure would be used for a further combined strategy.

4.1 First level: By individual measures

To illustrate the results of a series of BERs, the first level analysis is presented in two parts: one for HVAC systems exclusively and a separate analysis for the rest of measures.

4.1.1 HVAC retrofits

Office

The best exergy performance was obtained through the use of H32: boiler plus a MVHR system, which achieved an HVAC exergy efficiency of 19.3%. The final heating product cost was 0.14 £/kWh, while the cooling product was 0.25 £/kWh.. The system also achieved the best exergoeconomic performance with an $Exec_{CB}$ of £3.23/h (well below the £6.54/h of the baseline case). The total capital cost for the system was £66,693 with a DPB of 6.4 years. In addition, designs based on GSHP present the lowest exergy destructions and primary exergy input. The GSHP with underfloor heating (H21) also achieved a good exergoeconomic performance with an $Exec_{CB}$ of £5.42/h, but requiring a much higher capital investment at £409,564 providing a DPB of 34.9 years.

H24: PV/T system presented the highest NPV due to the additional income from both government incentives schemes for the generation of renewable electricity and hot water. The main drawback associated with this design is the high capital investment required (£873,200). However, exergoeconomic analysis highly penalises this design due to the fact of high capital costs, resulting in a $Exec_{CB}$ of £11.30/h. In terms of thermal comfort, high exergy systems (condensing gas and biomass boilers) with underfloor heating (H26, H29 respectively) provided the best performance. Fig. 11 shows the results for all the analysed HVAC systems, displaying the best solutions in the Pareto front. All the systems located inside the dotted square represent an improvement in both the exergoeconomic cost-benefit and occupant thermal comfort indicators.

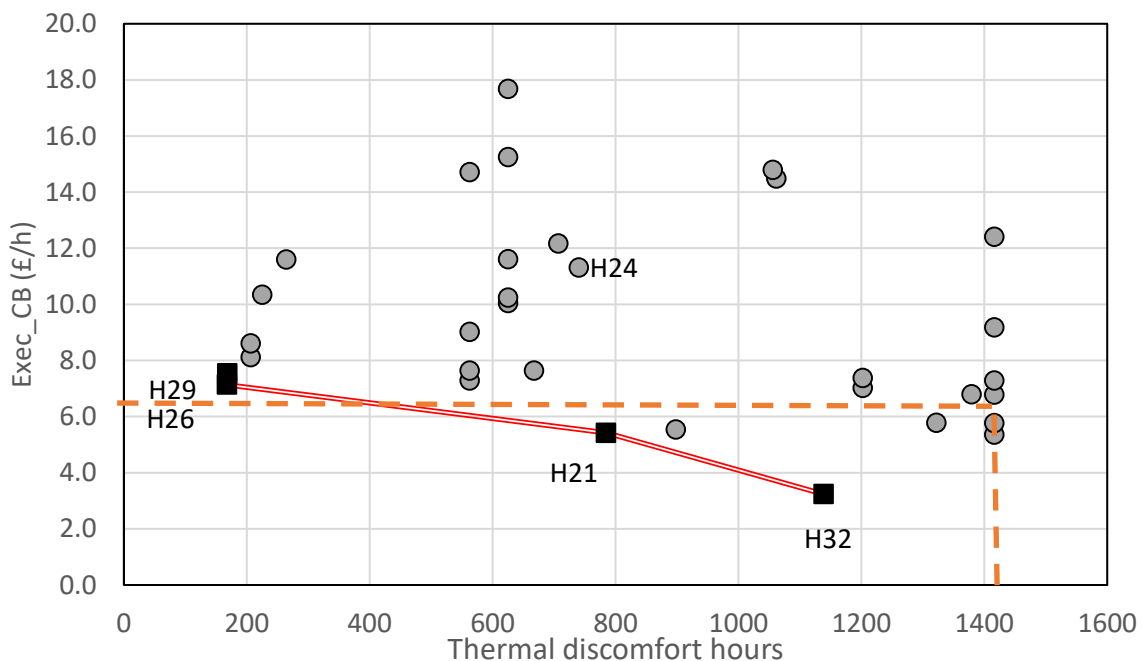


Fig. 11 A/C Office: HVAC systems $Exec_{CB}$ performance against thermal discomfort

Primary School

For the school case, H32: condensing gas boiler + CAV + MVHR and H16: district heating + underfloor system presented the best thermodynamic performance with exergy destructions reduction of up to 80%, however both failed to provide major thermal comfort improvements. The final heating product cost for H32 and H16 was £0.26/kWh and £0.65/kWh, representing an improvement from the base case (£1.89/h). H32 also achieved the best exergoeconomic performance with an $Exec_{CB}$ of £0.44/h (compared to the £2.89/h for the baseline case). The total capital cost for the system was £72,692 with a DPB of 10.7 years.

As a product of the RHI government incentive, the system with the highest NPV and lowest DPB is H31: micro-CHP system. However, the amount of electricity generated by the CHP that is used exclusively for heating purposes combined with its high capital cost has been penalised by exergoeconomic analysis, achieving an $Exec_{CB}$ of £6.17/h. Systems where incentives help to achieve low payback periods such as GSHP or waste-heat district systems can achieve better exergoeconomic results by using energy sources with lower energy quality levels. For thermal comfort performance, high exergy systems with large heated areas (wall heating) provided the best performance, but require larger investment costs for the emission systems. Fig. 12 shows the results for all the analysed HVAC systems, identifying five solutions in the Pareto front.

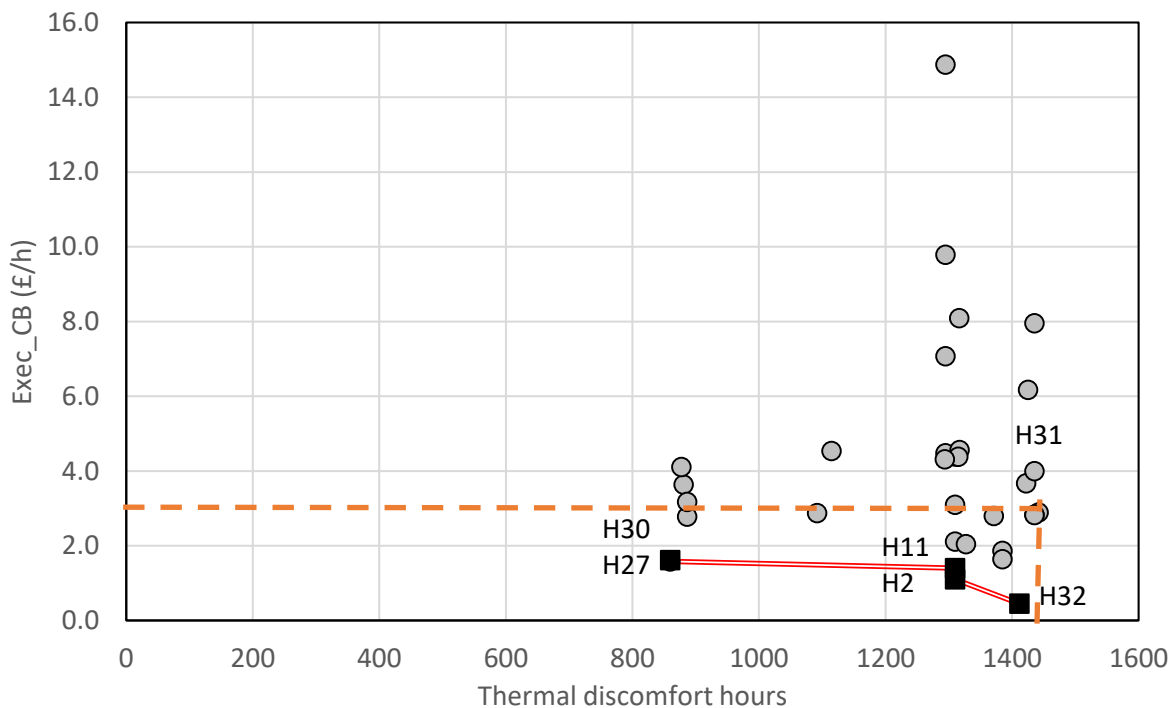


Fig. 12 Primary School: HVAC systems $Exec_{CB}$ performance against thermal discomfort

4.1.2 Non-HVAC retrofits

Non-HVAC solutions did not achieve any significant system exergy efficiency improvement, but could reduce total exergy destructions by lowering the building energy demand. The rest of the solutions have been differentiated into passive measures (insulation, glazing, sealing, and set-points) and active measures (lighting and renewables).

Office

For passive measures, insulation technologies such as corkboard (I6) and polyurethane (I1) achieved energy savings of 10% and reduced exergy destructions by 6%. Economically, the best performer was 0.03m of expanded polystyrene, with a capital cost of £14,348.7, a DPB of 11.6 years, and a $Exec_{CB}$ of £5.79/h. The envelope U-values ($W/m^2\cdot K$) achieved for this solution were: 0.38 for the wall, 0.43 for the roof and 0.25 for the ground. Triple glazing systems (air, argon, and krypton) achieved the highest energy savings among passive measures. However, economically none of the glazing systems reached a positive NPV during the project's lifetime (50 years) because of high capital investment cost. On the other hand, a hypothetical reduction of the infiltration rate achieved better economic and exergoeconomic results. An improvement of 60% of the uncontrolled infiltration achieved the highest NPV and an $Exec_{CB}$ of £4.95/h. It also achieved energy savings of 18% and exergy destructions reduction of 11%; however, it improved thermal comfort by just 1.5%. Moreover, changing set-points it is always a trade-off between obtaining better thermal comfort or extra energy savings. Set-points of 22 °C for heating, and 24°C for cooling provide the best comfort performance but did not produce any significant exergoeconomic change, both measures having an $Exec_{CB}$ of £6.54/h.

For the active measures, L3: LED-based lighting achieved the maximum minimisation of exergy destructions (15%) and the best $Exec_{CB}$ indicator (£4.95/h). This involved a capital investment of £177,343.8, resulting in a DPB of 23.7 years. For renewable systems, the only technology that achieved a positive NPV value and an improvement in $Exec_{CB}$ (£6.19/h) was R4: 20 kW wind turbine. Irreversibilities reductions were minimal as electricity were being used for the same end-use processes, where just a slight decrease can be seen at the 'Primary Energy Transformation' subsystem due to the lower fossil fuel utilisation for generation of electricity.

Fig. 13 shows the results for all the non-HVAC measures applied to the office archetype, locating those technologies that have better exergoeconomic and thermal comfort

performance. As individual measures and for the exclusive case of this office archetype, it is clear that minimising infiltration rate has the biggest impact on both indicators.

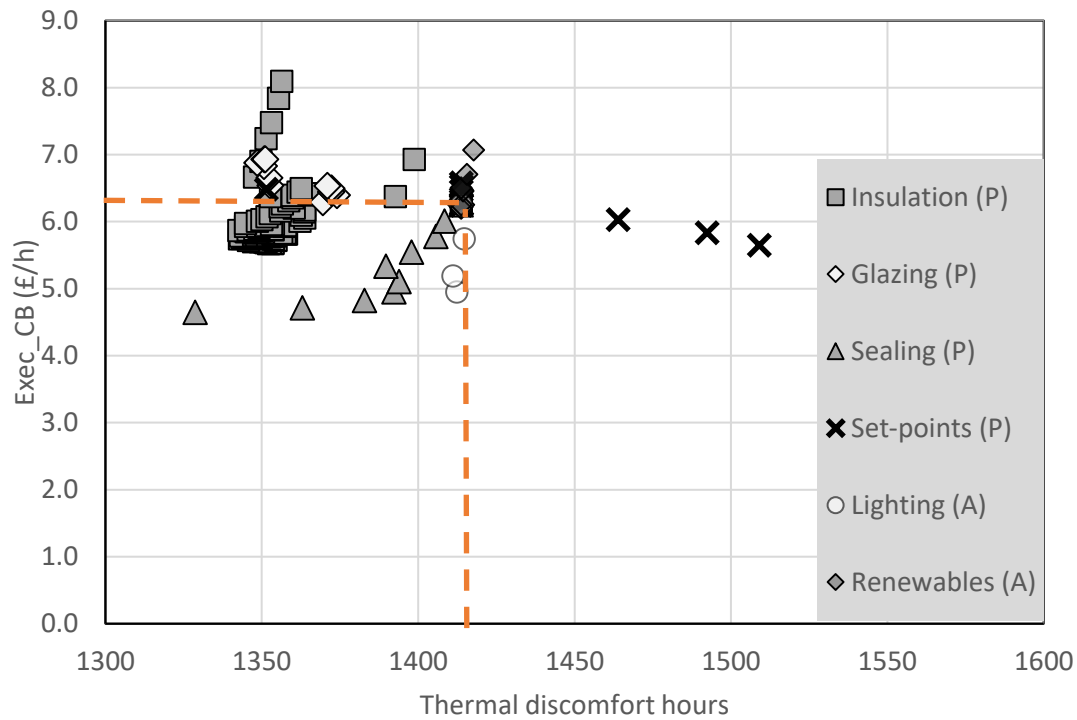


Fig. 13 A/C Office: All BERs (no HVAC) Exec_CB performance against thermal discomfort

School

For the school case, almost all insulation measures presented an improvement in the analysed indicators. Glass fibre with a thickness of 0.085m produced the best overall performance, achieving a DBP of 13 years with an investment of £20,105, along the lowest $Exec_{CB}$ among insulation measures with a value of £2.24/h. The U-values ($W/m^2 \cdot K$) for this measure were 0.33 for the wall, 0.37 for the roof and 0.32 for the ground. As in the case of the office, glazing systems failed to provide any considerable energy savings and also performed poorly in terms of economic indicators where seasonal occupancy does not justify individual installation. For airtightness measures, an improvement of 70% in infiltration rates produced the best $Exec_{CB}$ with a value of £2.53/h, while improving thermal comfort by 4%. Low setpoints ($18^\circ C$) achieved good exergoeconomic performance ($Exec_{CB} = £2.31/h$) but with a comfort decrease of 1%. On the other hand, a setpoint of $22^\circ C$ has poor exergoeconomic performance ($Exec_{CB} = £3.70/h$), but increases thermal comfort by 21%.

Among lighting technologies, LED system achieved the best energy results; however, exergoeconomic indicators did not significantly improve compared to the baseline. For

renewable measures, exergy destructions were not minimised due to the fact that electricity was still being used for the same end-uses. Analysing the NPV, only the R4: 20 kW turbine achieved a positive value and an $Exec_{CB}$ of £2.70/h. The installation of stand-alone PV panels without the improvement on other areas provide poor exergoeconomic results. Fig. 14 shows the results for all the non-HVAC measures applied to the school archetype, locating those that have better exergoeconomic and thermal comfort performance compared to the baseline case.

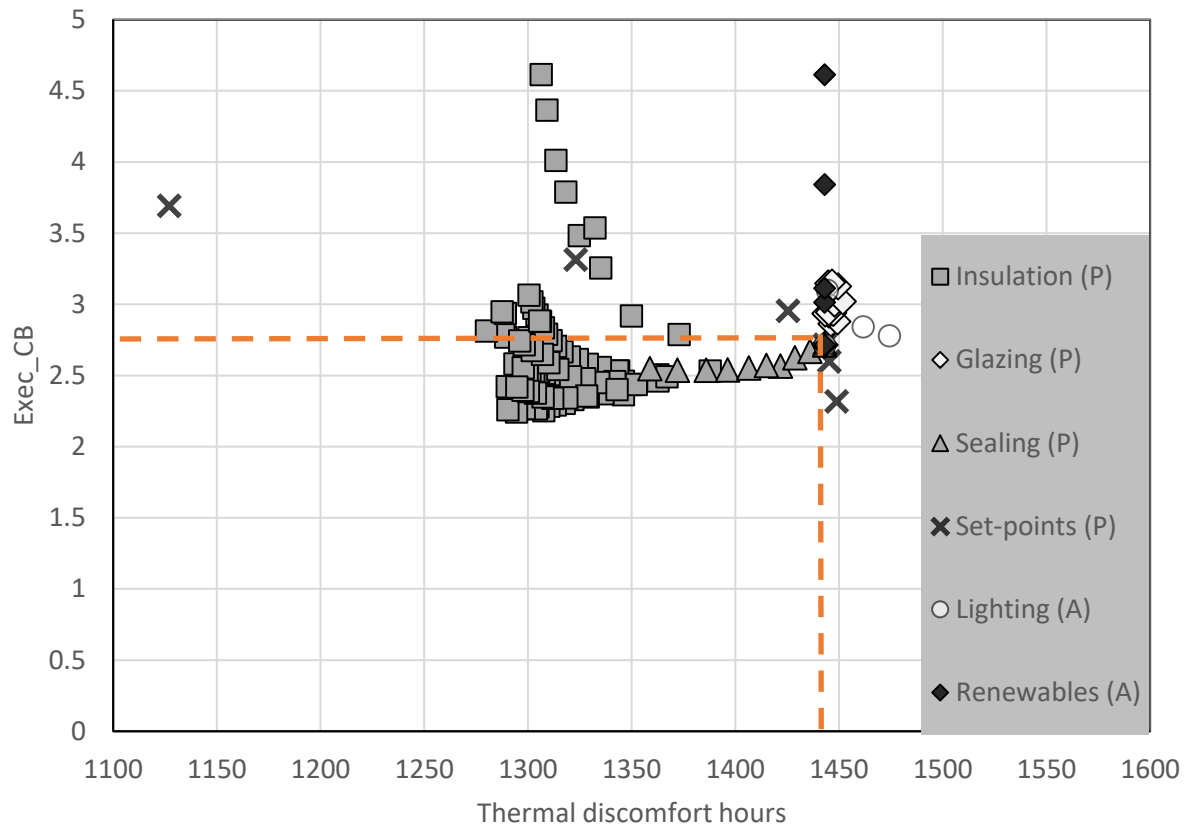


Fig. 14 Primary School: All BERs (no HVAC) $Exec_{CB}$ performance against thermal discomfort

4.2 Further improvement: Combined Measures (2nd level)

Since the benefit of a combined retrofit scenario is not the sum of individual benefits due to complex interaction of the building physics and its systems, deep BER packages were designed based on the investigated indicators. Table 9 shows the measures per technology type that comprise the deep retrofit packages as well as the required investment. The capital cost ratio between passive and active measures was found to be around 20% for both retrofit designs.

Table 9 Deep energy retrofit characteristics for both buildings

Technology	Primary School	Investment (£)	A/C Office	Investment (£)
<i>HVAC system</i>	Biomass Boiler (194 kW)	40,287.9	GSHP (127 kW)	153,388.9
<i>Emission system</i>	VAV	18,200	LT Underfloor	95,426
<i>Insulation</i>	Glass fibre Thickness: 8.5 cm	20,813.4	EPS Thickness: 7cm	19,514
<i>Glazing system</i>	Double pane 13mm (air gap)	47,324.5	Double pane 13mm (air gap)	141,201
<i>Sealing (ach)</i>	0.3	56,924.8	0.4	54,327
<i>Set-points (Heat/Cool)</i>	22 (no cooling)	--	21 and 24	--
<i>Lighting</i>	LED	128,829.5	LED	177,343.8
<i>Renewable systems</i>	PV: 25% roof (216 m ² –43 kWp)	342,588	PV: 25% roof (285 m ² –57 kWp)	259,200
	Wind: 20 kW	80,000	Wind: 20 kW	80,000
<i>Total</i>		734,968.1		980,401.3
<i>Passive/Active Investment Ratio</i>		0.17		0.22

4.2.1 Results

Both packages achieved energy savings of around 70% and an improvement of thermal comfort of 66% and 22% for the school and office, respectively. In addition, reductions of exergy destructions were achieved at a rate of 48.9% for the school and 46.4% for the office. As shown in Fig. 15, exergy destruction cost rates were also minimised, promoting a reduction from £2.89/h to £1.28/h for the school (56%) and from £6.54/h to £5.08/h for the office (22%).

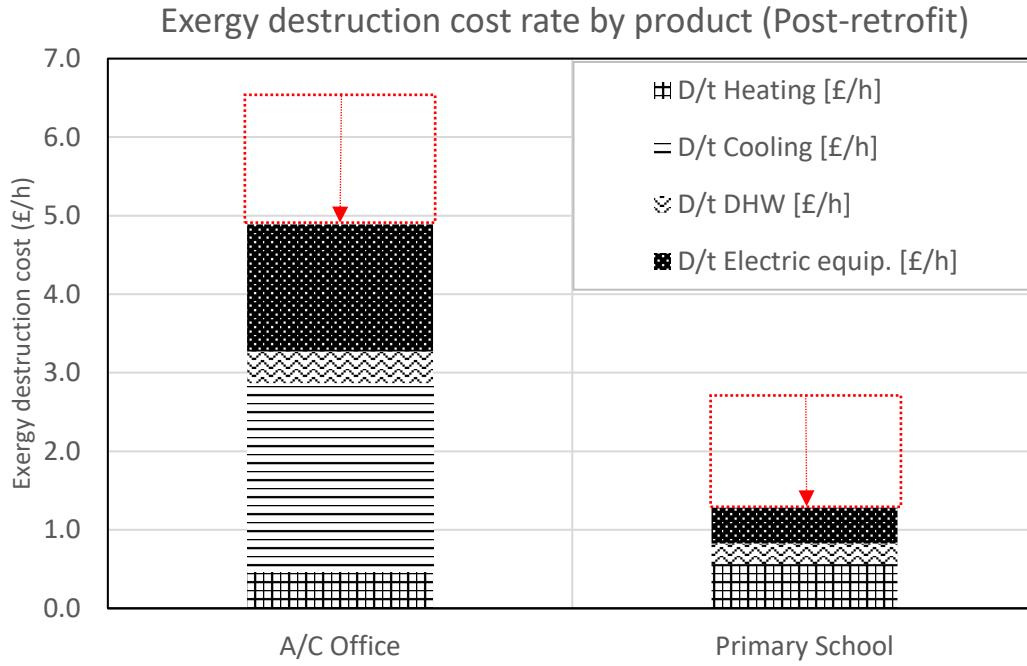


Fig. 15 Exergy destruction cost rate per product type (Post-retrofit)

The $Exec_{CB}$ indicator also presented a lower value than the baseline exergy destructions cost. Although in both cases, these were not as high as expected due to high capital investment (£369/m² and £379/m² for the school and office, respectively) and a lower than expected annual revenue. For the school, the $Exec_{CB}$ was £1.96/h with a DPB of 84 years, while for the office the $Exec_{CB}$ was £5.07/h with a DPB of 61 years. These long payback periods show how typical economics does not account for exergy savings and exergy efficiency. This supports the case for developing exergy-based taxation and incentives, which will encourage the design of buildings with lower exergy destructions footprint. Overall, the proposed exergoeconomic cost-benefit indicator presented a good correlation with typical economic indicators, suggesting that the former could also be reliable for decision making.

Finally, Table 10 summarises all the main outputs for the combined measures compared against the baseline scenarios. As it can be noticed, thermodynamically deep BER designs were able to reduce final product price for heating and cooling streams.

Table 10 A comparison of energy, exergy, and exergoeconomic values for pre-retrofit and post-retrofit buildings

Properties	Primary School			A/C Office		
	Base Case	Deep Retrofit	% Variation	Base Case	Deep Retrofit	% Variation
<i>Energy use (EUI)</i> (kWh/m ² -y)	187.86	79.93	-75.3	288.54	120.6	-67.2
<i>Annual emissions</i> (TonCO ₂)	214.8	20.9	-90.3	285.6	133.9	-53.1
<i>Thermal Discomfort</i> (hrs)	1443	490	-66.0	1414	1101	-22.1
<i>Energy bill (after incentives)</i> (£)	19449.3	-2121.1	-110.1	59625.3	24494.7	-58.9
<i>Exergy input</i> (MWh)	533.0	276.8	-48.1	1440.8	891.2	-38.1
<i>Exergy destructions</i> (MWh)	489.4	246.1	-49.7	1228.2	713.2	-41.9
<i>Exergy efficiency HVAC</i>	1.5%	2.6%	+1.1	5.1%	15.9%	+10.8
<i>Exergy efficiency DHW</i>	6.2%	5.7%	-0.5	8.7%	2.8%	-5.9
<i>Exergy efficiency Electric equipment</i>	15.1%	16.9%	+1.8	18.9%	22.2%	+2.3
<i>Exergy efficiency Whole Building</i>	8.2%	11.1%	+2.9	14.8%	20.0%	+5.2
<i>Exergy price fuel-prod HEAT (£/kWh)</i> { <i>r_k</i> }	0.03->1.86 {61.11}	0.04->1.29 {31.22}	-31.8	0.03->0.45 {13.86}	0.12->0.19 {0.59}	-54.8
<i>Exergy price fuel-prod COLD (£/kWh)</i> { <i>r_k</i> }	----- {---}	----- {---}	--	0.12->3.11 {24.89}	0.12->0.47 {2.90}	-84.8
<i>Exergy price fuel-prod DHW (£/kWh)</i> { <i>r_k</i> }	0.03->0.44 {13.72}	0.04->0.58 {13.62}	+31.8	0.03->0.55 {17.49}	0.12->1.65 {12.8}	+200.0
<i>Exergy price fuel-prod Elec (£/kWh)</i> { <i>r_k</i> }	0.12->0.31 {1.60}	0.12->0.28 {1.33}	-9.7	0.12->0.25 {1.07}	0.12->0.21 {0.76}	-12.5
<i>D cost destructions</i> (£/h)	2.89	1.22	-57.8	6.54	4.89	-25.2
<i>Capital investment</i> (£)	--	£734,968.1	--	--	£980,401.3	--
<i>Z</i> (£/h)	--	3.15	--	--	4.20	--
<i>Annual revenue</i> (£/h)	--	2.46	--	--	4.01	--
<i>Exec_CB</i> (£/h)	--	1.96	--	--	5.08	--
<i>Exergoeconomic factor f_k (-)</i>	--	0.71	--	--	0.46	--

5. Sensitivity Analysis

5.1 Post-parametric study (3rd level)

A sensitivity analysis was performed to explore further optimisation of design characteristics. For this particular analysis, the building wall insulation was varied leaving the rest of the envelope intact.

School

As a result of increasing the glass fibre insulation thickness, an increment in total capital investment was obtained, even with the biomass boiler size reduction due to a lower energy demand (Fig. 16). Added to this, a slight reduction in discomfort hours was obtained.

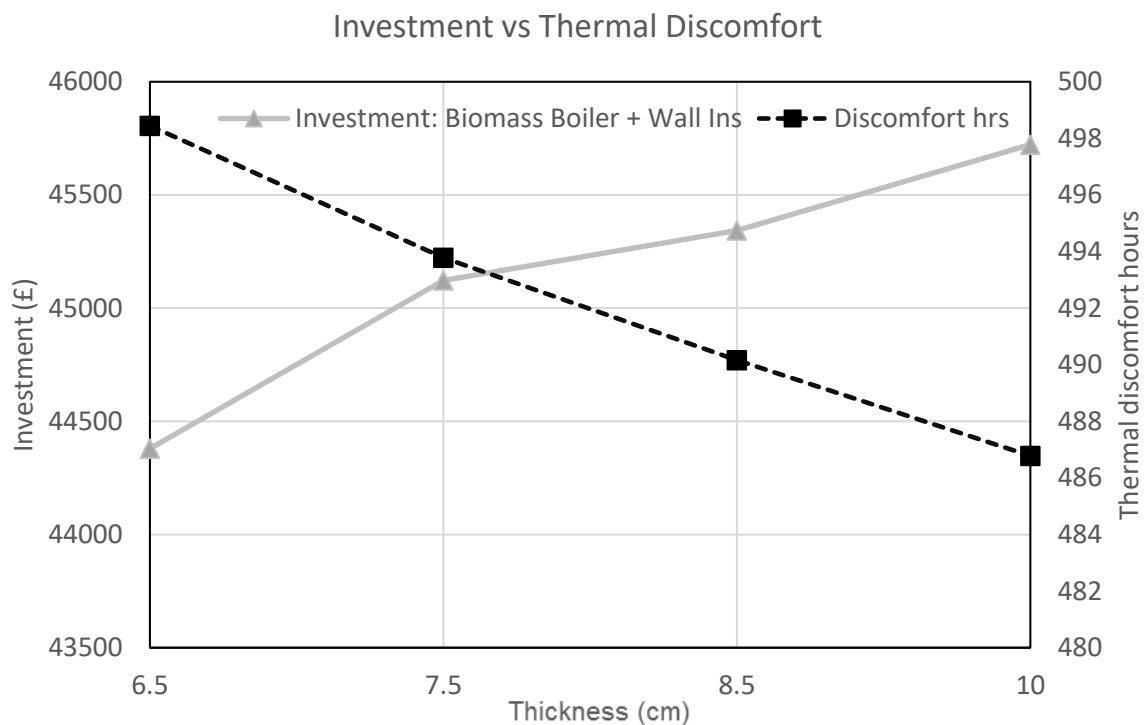


Fig. 16 Sensitivity analysis of glass fibre wall insulation for the School case. Investment and Discomfort hours

By increasing the insulation, a minimisation in both the energy use and exergy destructions was achieved (Fig. 17). The exergy destruction cost for heating ranges from £0.57/h for the lowest value of insulation to £0.53/h for 0.10m.

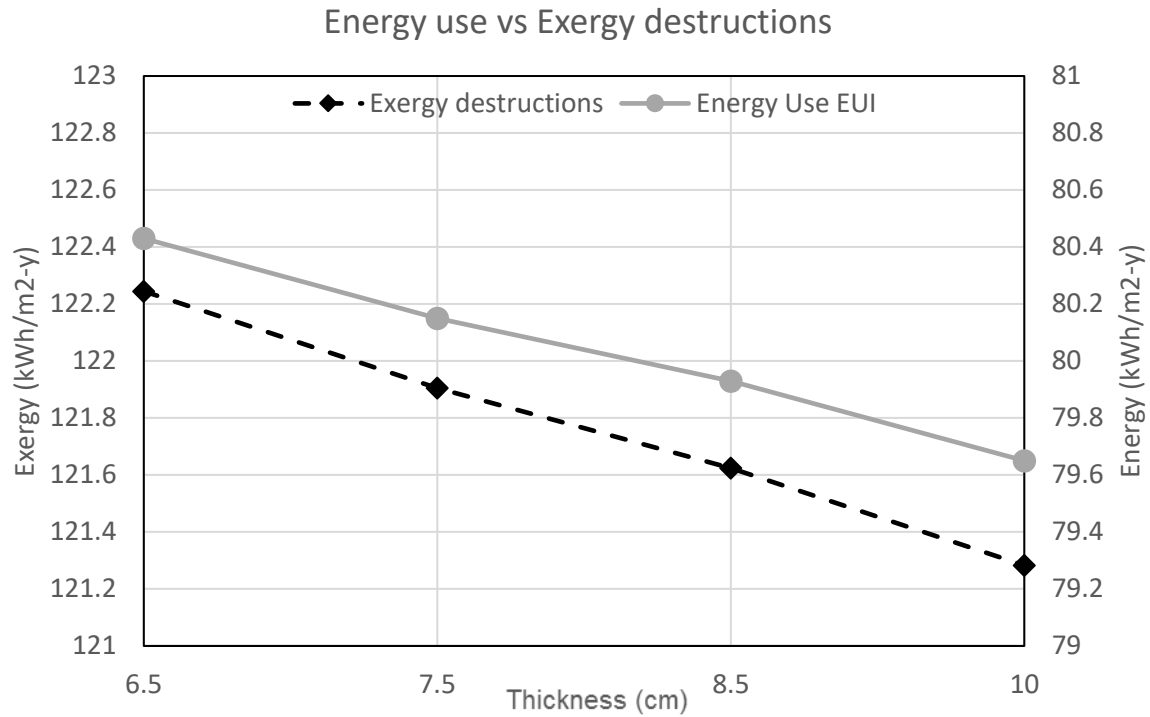


Fig. 17 Sensitivity analysis of glass fibre wall insulation for the School case. Energy use vs Exergy destructions

Office

For the office, the outputs are slightly different. By increasing the insulation, the total investment cost is reduced as the capital cost savings from downsizing the GSHP equipment exceed the extra investment for thicker insulation (Fig. 18). At 0.07m of EPS, the GSHP had a capacity of 127 kW, while for 0.15m of EPS, the GSHP size is reduced to 119 kW, requiring a lower investment cost. However, this increase in insulation negatively impacts thermal comfort due to overheating during summer months. However, DBPs are very similar for both extreme cases, ranging from 64 years for the lowest thickness to 60 years for the highest insulation level.

Investment and thermal discomfort

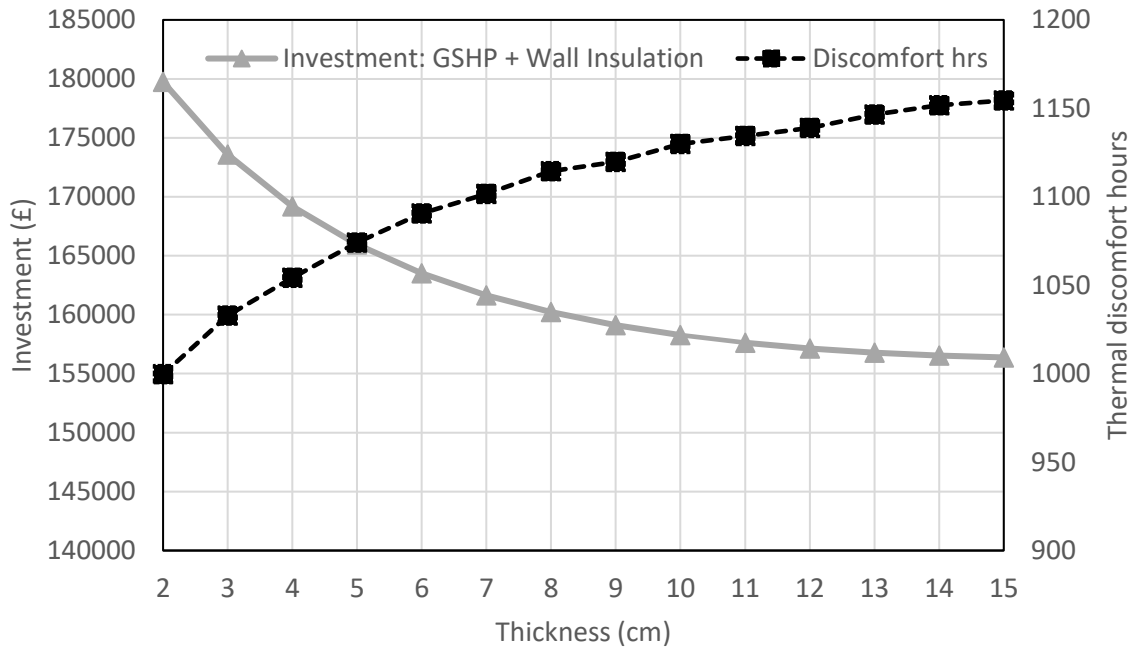


Fig. 18 Sensitivity analysis of EPS wall insulation for the Office case. Investment and Discomfort hours

Fig. 19 shows different behaviours for energy use and exergy destructions. On one hand, the increase of insulation leads to the reduction in total energy use, where savings in electricity for the operation of the heat pump in heating mode are greater than the increase of electrical demand for cooling. On the other hand, this is the opposite in exergy terms. An increase in electrical demand for cooling presents larger irreversibilities than exergy savings in the heating process, due to the lower exergetic efficiency for cooling processes in a temperate climate such as London. Therefore, other passive strategies such as natural ventilation or night cooling should be pursued to lower exergetic demand and increase efficiency. By decreasing insulation thickness from 0.07m to 0.02m, an increase in exergy efficiency from 18.3% to 18.9% could be achieved. In addition, the exergy destruction cost for the heating and cooling products combined is proportional to thickness insulation increase, going from £1.83/h for 0.02m to £2.19/h for 0.15m.

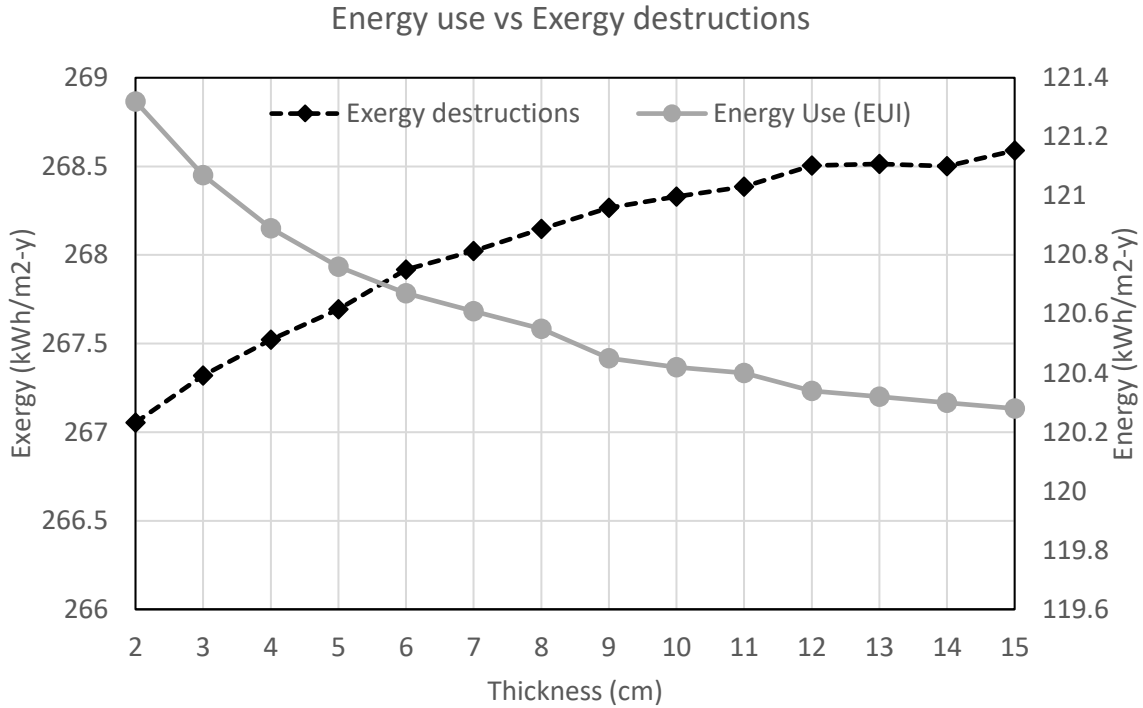


Fig. 19 Sensitivity analysis of glass fibre wall insulation for the Office case. Energy use vs Exergy destructions

6. Conclusions

Selecting BER measures that are able to deliver high exergy efficiency combined with low capital cost and high return of investment is still a challenge. This paper presented a way by which exergoeconomics could be integrated as a valuable decision-making support tool for improving BER design. The proposed method embeds thermoeconomic theory into BER practice through the development and integration of an exergoeconomic module into a retrofit oriented building simulation tool. In addition to this, a novel exergoeconomic cost benefit indicator, that considers the economics of energy use, the cost of exergy destruction, and the capital and revenue costs due to energy savings, was presented.

In typical practice, it is believed that buildings with better performance are those who tend to have a good passive design and a tighter envelope. But the results obtained for the specific case studies showed that active components (especially HVAC systems) have better energy, economic, exergy, and exergoeconomic performance, and are therefore more likely to improve overall thermodynamic performance. For this reason, before any major passive refurbishment is undertaken, findings suggest that active measures should be first considered.

Furthermore, deep energy/exergy retrofits were designed based on the developed exergoeconomic index. The office deep-BER achieved improvements in energy use of 67%, CO₂ emissions by 53%, thermal comfort by 22%, and reductions of exergy destructions by 42%. Also, overall exergy efficiency was improved from 14.8% to 20.4%. The school case presented similar results with the potential to generate income thanks to government incentives (RHI). School building exergy efficiency was improved from 8.2% to 11.1%. In both cases, final product cost for heating and cooling were notably reduced.

However, to achieve high thermodynamic performance, high capital investments were required showing that low exergy equipment is still expensive under current market conditions. For example, district systems do not seem economically viable due to lack of government incentives. In this sense, exergy based taxation and incentives could help unlock unconventional technologies and provide more flexibility in the design process, where high performance buildings combined with low exergy supply structures are key for a future sustainable development of the building sector. Other similar low exergy systems that showed high capital prices in the current market are heat pumps that work with low temperature lifting. Model exergy outputs showed that CHP and PV/T products, especially electricity, need to be used correctly, considering a supply-demand quality match in the design. Using electricity for space conditioning is a practice that should be avoided and heavily penalised. Finally, a post-parametric sensitivity analysis on the wall insulation thickness was performed to investigate the potential for additional improvement.

Exergoeconomics can be integrated into the design of BERs to provide more sustainable and efficient solutions. Further work in this area will integrate the developed exergoeconomic module into a multi-objective optimisation platform which will allow the modeller to perform a deeper exploration, and expect to achieve better solutions under energy, exergy, economic, and exergoeconomic objectives. In addition, further research will involve the application of the tool to real buildings. Finally, as part of the model's constant development, it is intended to verify and validate the outputs with similar studies.

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Nomenclature

A	area (m ²)
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BER	building energy retrofit
COP	coefficient of performance (W/W)
\dot{C}_D	exergy destruction cost (£)
\dot{C}_p	exergy cost balance (£/kWh)
c_{Pheat}	specific heat capacity (J/K)
c_f	average cost of fuel (£/kWh)
c_p	average cost of product (£/kWh)
C_{Pheat}	specific heat capacity (J/K)
CRF	capital recovery factor (£)
DPB	discounted payback (years)
En	energy (kWh)
EUI	energy use index (kWh/m ² -year)
Ex	exergy (kWh)
\dot{Ex}_D	exergy destructions (kWh)
\dot{Ex}_F	fuel exergy (kWh)
\dot{Ex}_P	product exergy (kWh)
Ex_{prim}	primary exergy (kWh)
Ex_{sun}	solar exergy (kWh)
$Exec_{CB}$	exergoeconomic cost benefit factor (£/h)
f_k	exergoeconomic factor (-)
F_p	primary energy factor (-)
F_q	quality factor (-)
G	incident solar radiation, (W/m ²)
i	interest rate (%)
m	mass flow rate (kg/s)
N	project lifetime (years)
NPV	net present value (£)
PW	present factor (£)
R	annual revenue (£)
r_k	relative cost difference (-)
SV	residual cost (£)
T_0	reference temperature (K)
T_i	room temperature (K)
TCI	total capital investment (£)
W	work (kWh)
\dot{Z}_k	capital investment rate (£/h)

Greek symbols

η_{gen}	energy efficiency (-)
ψ_{tot}	exergy efficiency (-)
Subscripts and superscripts	
col	collector
$cook$	cooking
dem	demand
dhw	domestic hot water
$elec$	electricity
gen	generation system
$hvac$	heating, ventilation, and air conditioning
i	i zone, equipment or energy source
k	building subsystem or component
$prim$	primary energy
PV	photovoltaic
sun	sun
t_k	time step
$therm$	thermal demand

Appendix A. Exergy analysis for renewable-based equipment

Direct solar systems:

To calculate the exergy of the incoming solar radiation Ex_{sun} to the equipment the following formula is used:

$$Ex_{sun}(t_k) = G(t_k) * A_{col} * \left(1 - \frac{T_0(t_k)}{T_{sun}}\right) \quad (A.1)$$

where G is the incident solar radiation, A_{col} is the collector surface area, T_0 is the reference environment, and T_{sun} is the sun's temperature, which is taken as 6000 K. Hence, the output of the collector Ex_{col} is the generation subsystem output and is calculated as follows:

$$Ex_{col}(t_k) = \dot{m}(t_k) * c_{pheat} \left[(T_{out}(t_k) - T_{in}(t_k)) - T_0(t_k) * \ln\left(\frac{T_{out}(t_k)}{T_{in}(t_k)}\right) \right] \quad (A.2)$$

where \dot{m} is the mass flow rate (kg/s), c_{pheat} is the carrier specific heat, T_{out} is the temperature provided by the collector, and T_{in} the return temperature to the collector. Finally, the exergy efficiency for solar collectors Ψ_{col} is obtained as follows:

$$\Psi_{col}(t_k) = \frac{Ex_{col}(t_k)}{Ex_{sun}(t_k)} \quad (A.3)$$

For hybrid PV/T panels, exergy efficiency Ψ_{PVT} is calculated as follows:

$$\Psi_{PVT}(t_k) = \frac{E_{PV}(t_k) + Ex_{col}(t_k)}{Ex_{sun}(t_k)} \quad (A.4)$$

where E_{PV} is the electrical energy generated by the panel (which has the same exergy value), Ex_{col} is the thermal exergy output, and Ex_{sun} is the incoming solar radiation.

Heat Pumps:

For heat pumps, we use the formula that only accounts for the exergy coming from electricity, thus the exergy content of the reservoir is considered as free exergy. Therefore, the efficiency Ψ_{HP} is calculated as follows:

$$\Psi_{HP}(t_k) = \frac{Ex_{th,dem}}{W} = \frac{\sum_{i=1}^n \left(En_{th,dem,i}(t_k) * \left(1 - \frac{T_0(t_k)}{T_i(t_k)} \right) \right)}{W(t_k)} = COP(t_k) * \left(1 - \frac{T_0(t_k)}{T_i(t_k)} \right) \quad (A.5)$$

Where $Ex_{th,dem}$ is the building thermal exergy demand, W is the electrical power input, $En_{th,dem}$ is the building thermal energy demand, T_0 is the reference temperature, T_i is the internal temperature, and COP is the heat pump coefficient of performance.

Appendix B. Characteristics of building retrofit measures

Table B.1 Characteristics and investment cost of HVAC systems

HVAC ID	System Description	Emission system	Cost
H1	Condensing Gas Boiler + Chiller	CAV	Generation systems
H2	Condensing Gas Boiler + Chiller	VAV	
H3	Condensing Gas Boiler + ASHP-VRF System	FC	
H4	Oil Boiler + Chiller	CAV	
H5	Oil Boiler + Chiller	VAV	
H6	Oil Boiler + Chiller	FC	
H7	Electric Boiler + Chiller	CAV	
H8	Electric Boiler + Chiller	VAV	
H9	Electric Boiler + ASHP-VRF System	FC	
H10	Biomass Boiler + Chiller	CAV	
H11	Biomass Boiler + Chiller	VAV	
H12	Biomass Boiler + ASHP-VRF System	FC	
H13	District system	CAV	
H14	District system	VAV	
H15	District system	Wall	
H16	District system	Underfloor	Emission systems
H17	District system	Wall+Underfloor	
H18	Ground Source Heat Pump	CAV	
H19	Ground Source Heat Pump	VAV	
H20	Ground Source Heat Pump	Wall	

H21	Ground Source Heat Pump	Underfloor	• £1200 per VAV
H22	Ground Source Heat Pump	Wall+Underfloor	• £35/m ² wall heating
H23	Air Source Heat Pump	CAV	• £35/m ² underfloor heating
H24	PVT-based system (50% roof) with supplemental Electric boiler and Old Chiller	CAV	• £6117 per Heat Recovery system
H25	Condensing Boiler + Chiller	Wall	
H26	Condensing Boiler + Chiller	Underfloor	Other subsystems: • £56/kW District heat exchanger + £6122 connection charge • £50/m for building's insulated distribution pipes
H27	Condensing Boiler + Chiller	Wall+Underfloor	
H28	Biomass Boiler + Chiller	Wall	
H29	Biomass Boiler + Chiller	Underfloor	
H30	Biomass Boiler + Chiller	Wall+Underfloor	
H31	Micro-CHP with Fuel Cell and Electric boiler and old Chiller	CAV	
H32	Condensing Gas Boiler and old Chiller. Heat Recovery System included.	CAV	

Table B.2 Characteristics and investment cost of lighting systems

Lights ID	Lighting technology	Cost per W/m ²
L1	T8 LFC	£5.55
L2	T5 LFC	£7.55
L3	T8 LED	£11.87

Table B.3 Characteristics and investment cost of renewable energy generation systems

Renewable	Technology	Cost
R1	PV panels 25% roof	PV: £1200/m ²
R2	PV panels 50% roof	
R3	PV panels 75% roof	
R4	Wind Turbine 20 kW	Turbine: £4000/kW
R5	Wind Turbine 40 kW	

Table B.4 Characteristics and investment cost of different insulation materials

Ins. ID	Insulation measure	Thickness (cm)	Total of measures	Cost per m ² (lowest to highest)
I1	Polyurethane	2 to 15 in 1 cm steps	14	£6.67 to £23.32
I2	Extruded polystyrene	1 to 15 in 1 cm steps	15	£4.77 to £31.99
I3	Expanded polystyrene	2 to 15 in 1 cm steps	14	£4.35 to £9.95
I4	Cellular Glass	4 to 18 in 1 cm steps	15	£16.21 to £72.94
I5	Glass Fibre	6.7, 7.5, 8.5, and 10 cm	4	£5.65 to £7.75
I6	Cork board	2 to 6 in 1 cm steps, 8 to 20 cm in 2 cm steps, 28 and 30 cm	14	£5.57 to £85.80
I7	Phenolic foam board	2 to 10 in 1 cm steps	9	£5.58 to £21.89
I8	Aerogel	0.5 to 4 in 0.5 cm steps	8	£26.80 to £195.14
I9	PCM (w/board)	10 and 20 mm	2	£57.75 to £107.75

Table B.5 Characteristics and investment cost of glazing systems

Glazing ID	System Description (# panes – gap)	Gas Filling	Cost per m²
G1	Double pane - 6mm	Air	£261
G2	Double pane - 13mm	Air	£261
G3	Double pane - 6mm	Argon	£350
G4	Double pane - 13mm	Argon	£350
G5	Double pane - 6mm	Krypton	£370
G6	Double pane - 13mm	Krypton	£370
G7	Triple pane - 6mm	Air	£467
G8	Triple pane - 13mm	Air	£467
G9	Triple pane - 6mm	Argon	£613
G10	Triple pane - 13mm	Argon	£613
G11	Triple pane - 6mm	Krypton	£653
G12	Triple pane - 13mm	Krypton	£653

Table B.6 Characteristics and investment cost for air tightness improvement considering baseline of 1 ach

Sealing ID	ACH (1/h) Improvement %	Cost per m² (opaque envelope)
S1	10%	£1.20
S2	20%	£3.31
S3	30%	£6.35
S4	40%	£10.30
S5	50%	£15.20
S6	60%	£20.98
S7	70%	£27.69
S8	80%	£35.33
S9	90%	£43.88

Table B.7 Cooling and heating indoor set points variations

Set-point ID	Set-point Type	Value (°C)	Cost
SH18	<i>Heating</i>	18	(-)
SH19		19	
SH20		20	
SH21		21	
SH22		22	
SC23	<i>Cooling</i>	23	(-)
SC24		24	
SC25		25	
SC26		26	
SC27		27	

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